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DEPARTMENT OF THE INTERIOR—U. S. GEOLOGICAL SURVEY
CHARLES D. WALCOTT, DIRECTOR

THE UNDERGROUND WATER OF THE ARKANSAS VALLEY IN EASTERN COLORADO

BY

GROVE KARL GILBERT

EXTRACT FROM THE SEVENTEENTH ANNUAL REPORT OF THE SURVEY, 1895-96
PART II—ECONOMIC GEOLOGY AND HYDROGRAPHY.

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1896

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THE UNDERGROUND WATER OF THE ARKANSAS VALLEY IN EASTERN COLORADO.

By G. K. Gilbert.

INTRODUCTION.

Underground water, like stream water, comes originally from the clouds. The rain is divided, after it reaches the ground, into three parts. One part flows away on the surface, making streams; a second part returns to the atmosphere through evaporation, being held by the soil as by a sponge until the air gradually absorbs it; the third part descends through the soil into various formations beneath and constitutes underground water. Some formations are full of small holes, or pores, into which water can enter. In sand, gravel, and some sandstones the pores are large enough to permit water not only to enter, but to flow through. In clay and shale the pores are so minute that water can pass only with extreme slowness. In most quartzites, limestones, and other compact rocks there are practically no pores, and water can pass only where they are broken. Underground water is acted on by gravity, just as stream water is, so that it flows; but its currents are slow, because there is much friction in traversing minute passages. It flows only in the porous, or pervious, formations, and its currents are guided by the impervious formations very much as a stream is guided by its channel. If, then, one knows the character, form, extent, and arrangement of the pervious and impervious formations, he can tell much about the underground currents of water—their sources, their depths, their volumes, their permanence, and even the quality of the water. Thus it is that the fundamental problems connected with underground water are related to the formations beneath the soil; or, in other words, they are geologic problems. There are, indeed, other considerations of great importance in connection with the utilization of such water, considerations depending on the nature of the use proposed, but in each locality the questions relating to natural occurrence are primary.

The writer has been engaged for three summers in the investigation of the geology of parts of the Arkansas Valley, and his attention has been directed chiefly to the determination of the composition, texture, thickness, arrangement, and distribution of the various formations. Not only are these characters the ones on which the distribution of

underground water depends, but the subject of underground water has been constantly in view as the leading economic purpose of the investigation. The present paper undertakes to present those results which bear on the more general problems of the utilization of underground water in the district.

For purposes of mapping, the Geological Survey has divided eastern Colorado into rectangular districts, bounded by certain meridians and parallels, and containing each about 950 square miles. The season of 1893 was devoted to detailed and thorough study of one of these rectangular districts, the Pueblo, lying between longitudes 104° 30′ and 105° and latitudes 38° and 38° 30′, the center being a few miles west of the city of Pueblo. In part of this work the writer was aided by Messrs. R. T. Hill and F. H. Newell. During the season of 1894 he had the assistance of Messrs. F. P. Gulliver and G. W. Stose, and the principal field of work was a similar district, the Apishapa, lying between longitudes 104° and 104° 30′ and latitudes 37° 30′ and 38°. The district includes the canyon of the Apishapa River and the lower half of the canyon of the Huerfano. In 1895 no detailed work was done, but a general reconnoissance was made from the head of the main Arkansas Valley, at the city of Canyon, to the eastern boundary of Kansas. The principal line followed was that of the Arkansas River, and the lower slopes of the valley were specially examined, but a number of excursions were also made to the north and south. One northward excursion touched Ordway and Antelope Springs, another Arlington, and a third Cheyenne Wells. Southward excursions reached the Purgatoire River at Bents Canyon, and Two Butte Creek near the butte that gives it its name. If the reader will note the points mentioned on a map of the State, he will readily understand that while the reconnoissance pertains to a belt of some width it by no means covers it, but touches it here and there.

TOPOGRAPHY OF THE DISTRICT.

As the following pages are intended primarily for the residents of the district described, a class whose habits of life tend to give them a broad acquaintance with their geographic surroundings, an extended account of the topography of the valley is not required.

The Great Plains are bounded at the west and the Rocky Mountains at the east by a belt of foothills, which in general runs from north to south. There are, however, many local curves and angles, and one of these affects the Arkansas Valley. Twenty miles south of Colorado Springs the line of foothills turns sharply westward for 20 miles, and then, near Canyon, swings quickly to the south and southeast, holding the latter course for 40 miles (see fig. 45). Within this flexure is a triangular tongue of the plains country, half surrounded by mountain ranges. The Arkansas River, gathering its waters from many a spring

and snowdrift in the mountains, passes to the plains at the narrow end of this tongue, traverses its middle, and flows eastward. Its principal affluents outside the mountains are Fountain Creek, rising in high mountains west of Colorado Springs; St. Charles River, draining Greenhorn Mountain and neighboring uplands; Huerfano River, draining Huerfano Park, a more southerly embayment of the Rocky Mountain front; Apishapa River, flowing from Spanish Peaks; and Purgatoire River, rising on the eastern slope of the Culebra Range. Of these mountain-born streams, the Fountain alone traverses the northern slope of the Arkansas Valley and holds a southerly course; the others flow on parallel lines toward the northeast. All tributaries east of the Fountain and the Purgatoire head within the plains.

For half of its course between Canyon and Pueblo the Arkansas is closely hemmed in by rock bluffs 200 feet high, with cliffs of limestone at top. Elsewhere its immediate valley is more open, usually with a

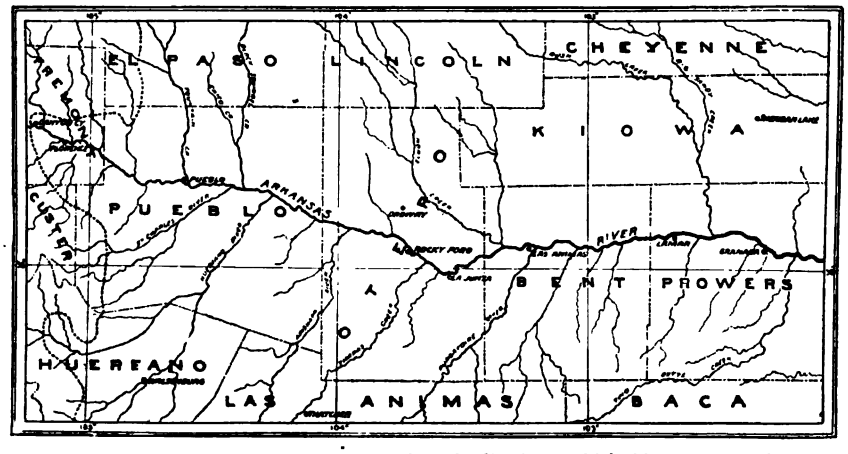


FIG. 45.—Map of part of Colorado, including the district to which this report pertains.

sharp ascent on one side to a gravelly mesa, and a long, gradual slope on the other. Farther back the ascent is broken by terraces of gravel or sand or by tracts of clayey bad lands, and here and there by rocky cliffs and mesas. East of the Fountain the northern slope is characterized chiefly by broad, gently undulating plains, illustrating the typical character of the Great Plains region. On the southern slope similar plains occur east of the Purgatoire, but the topography is in general more accented. The Purgatoire runs for 50 miles in a canyon between sandstone walls, and the Apishapa and Huerfano have shorter canyons of the same character.

At the city of Canyon the altitude of the river is 5,325 feet; at the Kansas line, 3,350 feet, the total fall being 1,975 feet. The distance by rail is 189 miles, but by river it is 218 miles, giving an average grade of 9 feet per mile. Considering the stream in three sections, the fall

from Canyon to Pueblo is 15 feet per mile, from Pueblo to La Junta 8 feet, from La Junta to the Kansas line 7.3 feet. In ascending northward or southward from the main stream the rise is more rapid. On the lines of main tributaries it averages about 25 feet per mile for the first 50 miles, and the general rise of the intervening slopes is 30 feet per mile.

GEOLOGY OF THE DISTRICT.

The principal rocks are shales, sandstones, and limestones, which alternate with one another in a series of layers. Each layer or formation is very broad, extending for scores or hundreds of miles, but is of comparatively small thickness. One rests on another like the leaves of a book. Each formation was originally a soft sediment at the bottom of a sea or ocean. The shale was mud; the sandstone was sand; the limestone was limy ooze. These sediments were brought to the ocean from neighboring lands by rivers, and were spread over the ocean bottom by ocean currents. The extent of the ocean was changed from time to time, and changes occurred in the character of the rivers; and in consequence of these changes the character of sediment was not always the same. Mud, limy ooze, and sand were deposited in alternation, building up a varied series of layers. Afterward, by pressure or by chemical changes, the sediments were hardened into rocks such as are now found.

The character of the lower members of this series of formations is not well known, and with reference to the problem of water supply is of little importance. It will be necessary here to speak only of the Juratrias and the Cretaceous rocks. The Juratrias are the older, and underlie the Cretaceous.

JURATRIAS ROCKS.

These consist chiefly of sandstone, conglomerate, and shale, but include also beds of limestone and gypsum. The number, character, and thickness of the formations vary greatly from place to place. In the foothills near Beulah the series includes a rapid alternation of sandstone, conglomerate, and shale, all characterized by a deep-red color, and the total thickness is there about 2,000 feet. At the northeast, where Turkey Creek crosses the foothills, this series is thinner and has less conglomerate, but retains the red color. Above it are shales of various brilliant hues—orange, white, blue, green, and chocolate—mostly with a considerable admixture of sand. Interspersed among them are several layers of yellowish sandstone, and also several beds of gypsum, either white or mottled with gray. The entire thickness of this upper series is over 500 feet. On the Purgatoire, above Bents Canyon, the most prominent member is a brilliant-red sandstone, about 150 feet thick, beneath which are softer beds of the same color and of greater thickness. Above it are pale-greenish shales, inter-

bedded with white and gray gypsum, white limestone, and, toward the top, with orange sandstone, the whole having a thickness of 220 feet. On Two Butte Creek, near Two Buttes, the most conspicuous bed is again a red sandstone, 150 feet thick. Below this are 150 feet of red shales, and these rest upon sandstones and shales of various dark hues. Above the red sandstone are 50 feet of red shale, and then occur gray sandstones and gray sandy shales in alternation for several hundred feet, the upper limit not having been determined.

In a general way, the Juratrias rocks of this region are characterized by considerable thicknesses of red strata, and as beds of that color seldom appear in the overlying formation they may be used for the identification of the Juratrias series wherever it is penetrated by the well-borer's drill.

Except in the immediate vicinity of the mountains, the sandstones of the series are of such fine texture as to prevent the circulation of water, and the shale, limestone, and gypsum beds are impervious. No successful wells have obtained their water from these rocks; and as there are no rocks beneath them which have yielded fresh water, any well borer of the Arkansas Valley who has penetrated 50 feet of red rocks may safely conclude that deeper exploration will prove unprofitable.

CRETACEOUS ROCKS.

Above the Juratrias beds is a great system of formations called Cretaceous. There is reason to believe that in several portions of the Arkansas Valley the deposition of sediment was interrupted after the Juratrias and before the Cretaceous. In those places the sea bottom was uplifted so as to constitute land, and the Juratrias sands and clays were partly washed away by rains and rivers before the ocean returned and other deposits were made. During the earlier stages of Cretaceous deposition there were also variations in the geography of land and sea, the coast line shifting to and fro; but this period was comparatively brief, and afterward the ocean held uninterrupted sway for an immense period, during which several thousand feet of deposits were accumulated.

The deposits have been classified in five subdivisions or groups, as given below. The name of the highest is placed uppermost, and the others in order, just as they overlie one another in nature; but they are numbered from below upward, so that the numbers represent their order in point of time, the lowest having been first made and the highest last.

5. Fox Hills group.
4. Pierre group.
3. Niobrara group.
2. Benton group.
1. Dakota group.

DAKOTA GROUP.

The Dakota group contains so much sandstone that it is frequently called "the Dakota sandstone," and in this respect it is strongly contrasted with the other Cretaceous groups, which in this district consist chiefly of shale. It also differs from the other members of the system in that it exhibits considerable variability from place to place, while the others are more nearly uniform in all parts of the district.

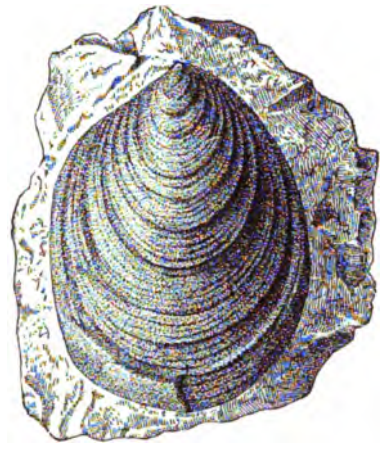
The Dakota sandstones are prevailingly of a yellowish-gray color. Some of the lower members, especially in the region of the foothills, are nearly white, and some of the upper members at the extreme east are of a dark-gray color, changing to a deep brown, almost black, on weathered surfaces. At the east the surface colors of lower beds include brilliant tints, especially orange, but the colors of fractured surfaces are usually dull and rather pale. There are also notable variations in texture. The upper layers are usually close textured; that is, the original pores between the sand grains are well filled with cement, so that the rock is but slightly porous and does not permit a free circulation of water. The lower beds are more open in texture, and are in general somewhat coarser, especially in the region of the foothills. Their open texture is due to the fact that but little cementing material has been introduced. The rock is feebly coherent, so that when it is encountered in boring it is readily reduced to sand by the blows of the drill, and is ordinarily described by the drillers as sand rather than as sandstone. In the region of the foothills the lower sandstones often contain many small pebbles, so as to approach conglomerates in character. In many of the beds the iron compounds which constitute their coloring matter seem to be disseminated in particles, giving to the fractured surface a speckled appearance.

Between the sandstones are shales, usually light or dark gray and somewhat arenaceous. They contain many shreds of vegetable tissue changed to coal, and at certain horizons this carbonaceous matter is so abundant as to render them nearly black. Some of the shales are also locally of a greenish-brown color. In the neighborhood of the mountains fully four-fifths of the group is of sandstone, and the only important shale bed is near the top of the series. In the eastern part of the district thick shale beds alternate with sandstones throughout the group, and their total thickness is probably greater than that of the sandstones. In all localities the uppermost sandstone beds are thin and alternate with gray shales, similar to those of the Benton group lying next above. Some of the shales in this transition zone have been found to have the qualities of fire clay.

The sandstones of the Dakota group are the chief water-bearing rocks of the district, and all artesian flows are obtained from them. They are therefore of peculiar importance in the present connection,

A CHARACTERISTIC EXPOSURE OF THE GREENHORN FORMATION NEAR THATCHER, COLORADO.

From photograph by F. P. Gulliver.



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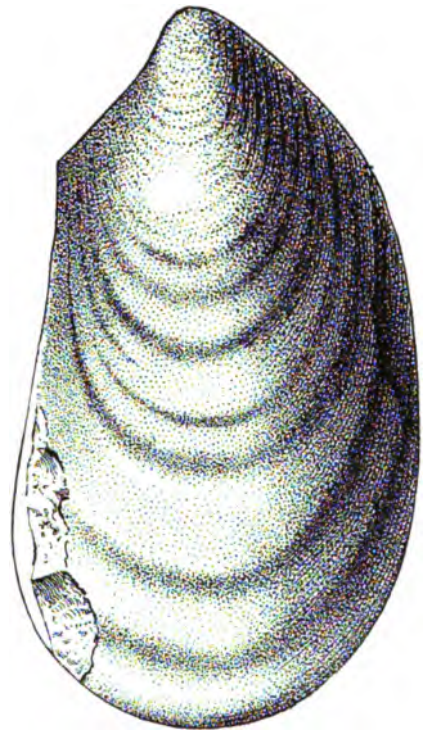

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INOCERAMUS LABIATUS, A FOSSIL BIVALVE SHELL OCCURRING IN ABUNDANCE IN SOME LAYERS OF THE GREENHORN FORMATION.

Fig. 1. A small individual, in which the concentric ridges of the shell are unusually strong.
Fig. 2. An individual of moderate size.

and it will be advantageous to give attention to the circumstances under which they were deposited.

The material of all sediments which gather at the bottom of seas is derived from the waste of adjacent land surfaces, and is transported from the one region to the other by currents of water, chiefly the water of streams. Where rivers enter the sea their currents are gradually checked, and there is a sorting of the transported particles. The coarser particles fall to the bottom first; the finer are carried farther. Thus the sand grains accumulate near the shore and the mud particles at a distance from shore. Waves also cooperate in sorting and distributing. To a certain extent they attack the shore, and, loosening its material wash it away. They also drift the particles brought by rivers one way and another along coasts, building sand and sometimes gravel into beaches. The finer particles are by the same agitation sorted from the coarser, and they eventually come to rest in deeper water. The sand zone constituting and bordering the beach is a narrow belt as compared to the broad bottom which receives the fine sediments, and sandstones, resulting usually from the consolidation of beach sands, would be formations of small extent but for the fact that coasts migrate. The changes in the height of land, which through all geologic time have modified the geography of the earth, incidentally cause coasts to advance over and retreat from the slopes of the land, and the zone of sand accumulation is thus carried gradually to and fro, so that the resulting sand formation may in the course of time become as broad as the formations of mud and limy ooze.

We do not know the positions of the coast during the various stages of the Dakota sea, but the alternation of sandstones and shales seems to indicate that it was shifted to and fro over the same district a number of times. Its movements were probably irregular, and the mouths of sand-bearing rivers were not always in the same places, so that the distribution of sand within the formation is uneven. At any rate, great variety is found in the details of rock succession within the group. Where the formations now appear at the surface and are examined and measured, it is found that no two localities give precisely the same sequence. The textures of the beds are comparatively uniform, but their thicknesses vary rapidly from place to place, so that a measurement at one locality will not warrant prediction as to the precise thicknesses to be found at another locality a few miles away. The same differences appear when the records of well borings are compared.

The character of the group can therefore be given only in general terms. It consists of an alternation of sandstones and shales, the sandstones having much the greater thickness at the west and the shales somewhat the greater thickness at the east. The total thickness is greatest near the mountains, where it averages about 300 feet, and has a maximum near Beulah of over 500 feet. In the eastern part of the district it ranges from 200 to 250 feet.

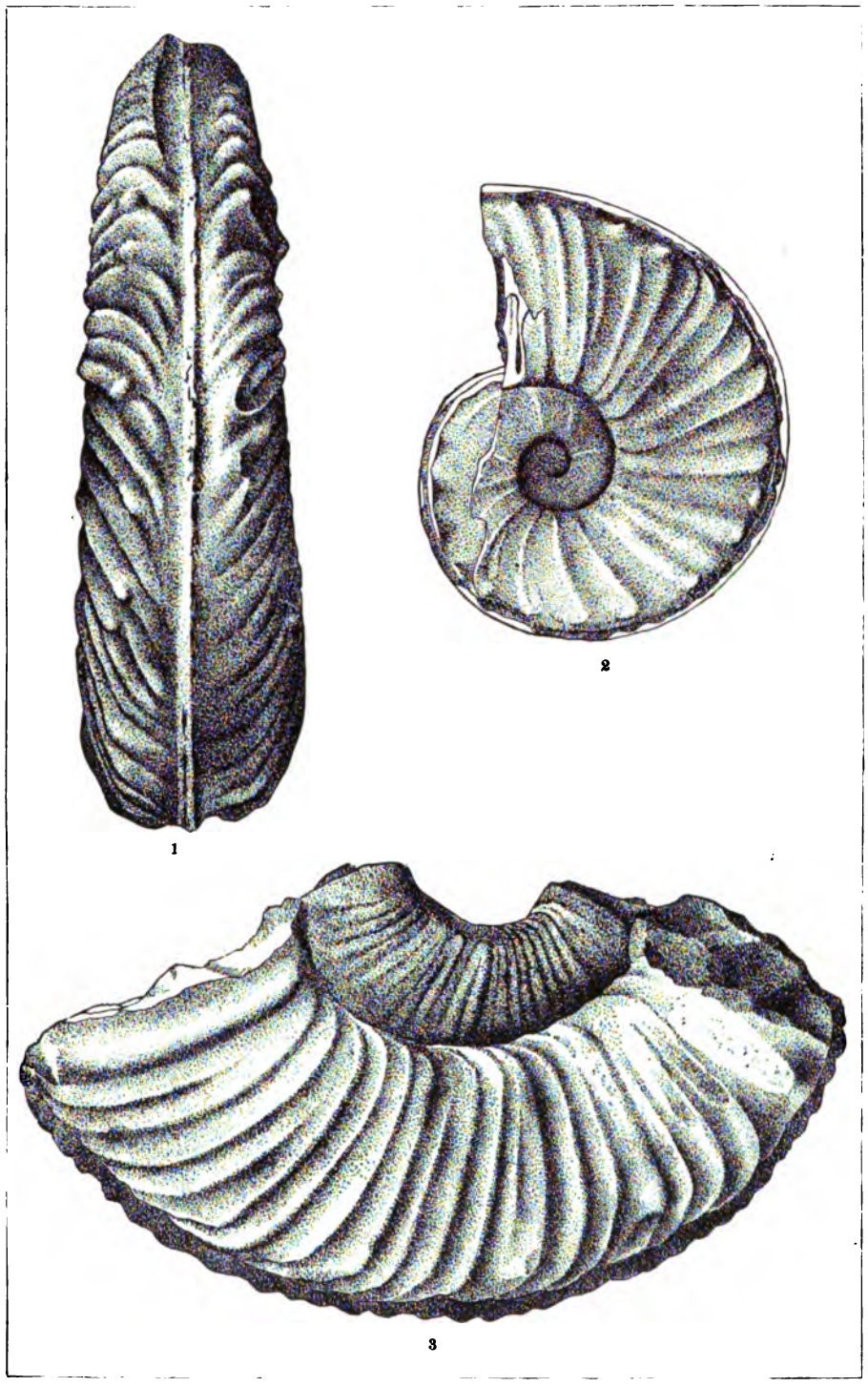
BENTON GROUP.

The members of this group are so regular within the limits of the district that many of them are everywhere recognized, and it has been found advantageous to consider the group as consisting of three distinct formations. These are:

3. Carlile shale.
2. Greenhorn limestone.
1. Graneros shale.

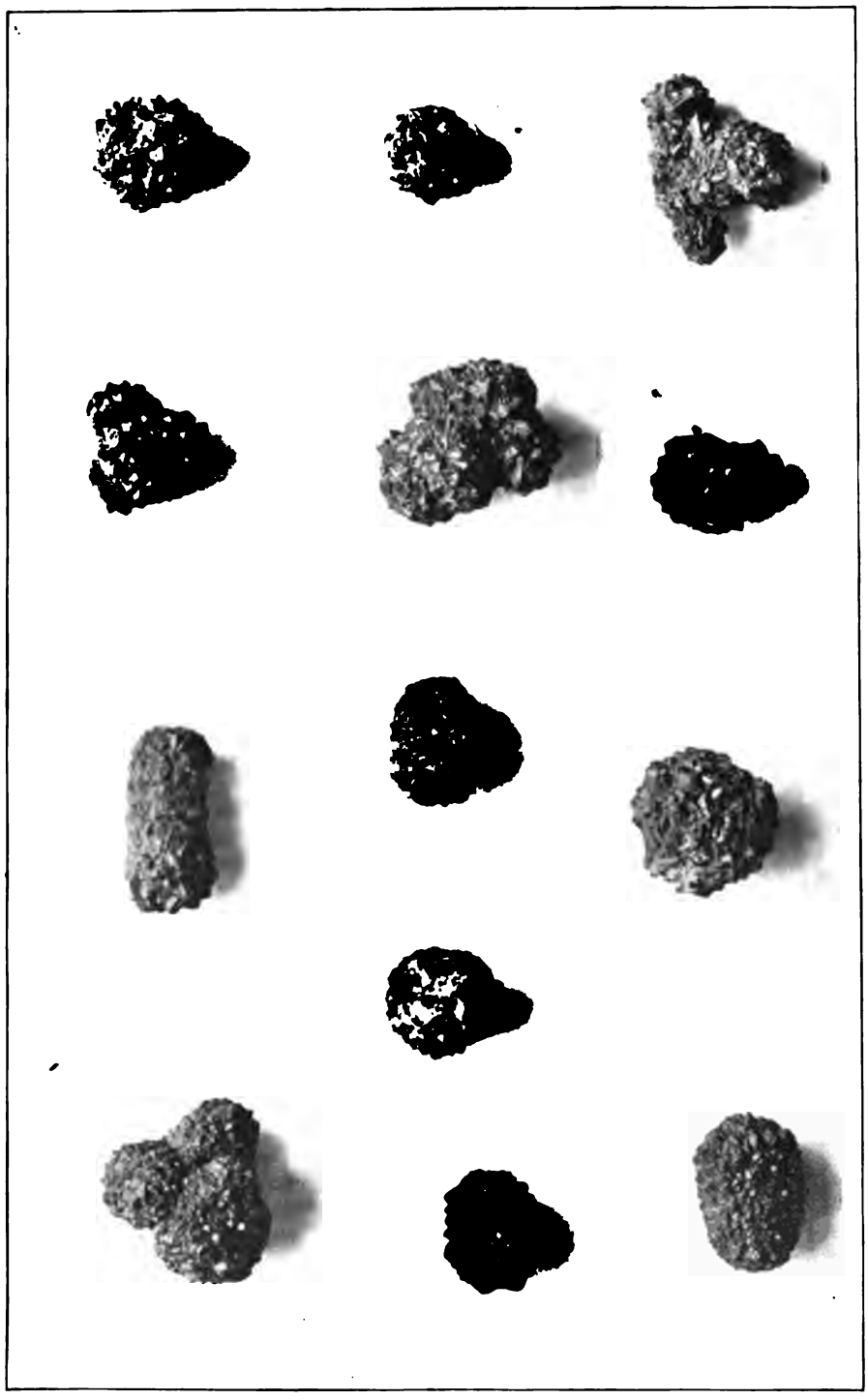
Graneros formation.—The Graneros shale rests directly on the uppermost sandstone of the Dakota group. Its thickness is from 200 to 210 feet. It is characteristically a laminated, argillaceous, or clayey shale with very little admixture of limy or sandy material. Where the shale has not been acted on by the weather it shows little tendency to split, and its lamination appears chiefly as a delicate marking of the surface. Brief exposure to the weather causes it to divide into thin flakes (laminæ), and prolonged weathering reduces it to clay. The middle third of the formation is dark gray, and thin bands of it are nearly black, as though highly bituminous. The upper and lower parts are medium gray. At various horizons, especially in the lower part, are thin beds of a white, structureless clay, resembling in appearance the fire clays which underlie coal seams, but a test shows that they have not the refractory property of fire clays. At various levels and localities are rows of calcareous concretions, and one of these rows, from 20 to 30 feet above the base of the formation, changes in certain districts into a layer of dark-gray limestone, with a maximum thickness of about a foot, which acquires by weathering a surface of bright orange. There are also, especially in the eastern part of the district, a few thin calcareous layers containing many fossil shells of small oysters. Twenty or thirty feet below the top of the formation is a rather persistent sandy limestone, only 1 to 3 inches thick, and this also contains fossils. In the eastern part of the district one or two other beds similar to this are found above it. These various exceptional layers have collectively a thickness of only 4 or 5 feet, so that, though very useful to the geologist in mapping the formation, they qualify but slightly its typical character as argillaceous shale.

Greenhorn formation.—This formation is 25 to 40 feet thick. It consists of strata of limestone, from 3 to 12 inches thick, separated by somewhat thicker shale beds. (See Pl. LVI.) The limestone is pale bluish-gray, fine grained and compact. Where exposed to the weather most of the beds are divided by vertical approximately parallel seams into plates from one-fourth of an inch to 1 or 2 inches in thickness. Of the thicker beds there is only one, near the bottom of the series, which does not exhibit this vertical structure. The shales have a light-gray color, are laminated, and contain more lime than do those of the



PRIONOCYCLUS WYOMINGENSIS, A FOSSIL SHELL FOUND AT MANY LOCALITIES IN THE DARK LIMESTONE AT TOP OF THE CARLILE SHALE AND JUST BENEATH THE WHITE TIMPAS LIMESTONE. THE SHELL IS COILED, SOMEWHAT LIKE THAT OF A LAND SNAIL.

Fig. 1. An edge view.
Fig. 2. A side view of a small individual.
Fig. 3. A side view of a fragment showing parts of two whorls of the coil.



NODULES OF MARCASITE. Natural size.

These are characteristic of the lower part of the Timpas limestone.

formations above and below. Among them are a few bands of white clay, like that mentioned as occurring in the Graneros shale.

Several of the limestone beds contain fossil shells in abundance, chiefly an oval bivalve, *Inoceramus labiatus*. Fossils are found also in other formations, but the assemblage of shells is different at different levels. This particular shell, although not entirely absent from some other formations, is abundant only in certain of the Greenhorn beds, and it thus serves as a sort of earmark by which those beds can be recognized and discriminated from certain other limestones for which they may be mistaken. A picture of *Inoceramus labiatus* is therefore introduced in Pl. LVII, in the hope that it may aid residents of the district in determining the geologic formations which occur at the localities in which they are interested. As will be explained later, the geologic formation found at the surface is an index of the depth to which it is necessary to drill in order to reach artesian water.

Carlile shale.—This shale is from 175 to 200 feet thick, and in its more general features resembles the Graneros. Its dominant color is medium-gray, and the middle third is darker. In the eastern part of the district its whole body is finely laminated and argillaceous. Farther west the upper fourth contains some sand, and its lamination becomes coarser or disappears. Portions of it, especially near the top, locally assume the character of sandstone, taking a light-yellow color. In the so-called Sand Hill, west of Pueblo and south of Rock Canyon, some layers of the sandstone are quarried for flagging and foundation rocks, and it is suitable for such use in a considerable district west and south of that place. While this rock is somewhat friable, it is not of open texture; the pores between sand grains are occupied by argillaceous material, so that it does not constitute either a reservoir or a conduit for underground water. Farther east the sandstone is often replaced by a purplish limestone, 2 or 3 feet thick, in which a large coiled shell, *Prionocyclus wyomingensis* (Pl. LVIII), is somewhat abundant, though so poorly preserved as usually to be seen only in outline.

Between 20 and 50 feet from the top of the formation are many calcareous nodules or concretions, ranging from a few inches to 4 or 5 feet in diameter. In form they are thick-ovoid to spherical. The outer layers have what is called the cone-in-cone structure, seeming to be made up of a system of interlocking cones with apices all pointing toward the middle of the concretion. The inner parts are of even, fine texture, and gray color. In all the larger specimens the interior is traversed by gaping cracks, which are partly or wholly filled by crystalline calcite. The first-formed calcite, lying adjacent to the walls of the cracks, is usually of dark tints, chiefly wine color; but the last-formed is white or transparent, and is often developed in large crystals of great beauty.

From 50 to 75 feet above the base of the formation there is sometimes

found, especially in the eastern part of the district, a thin limy bed with fossils.

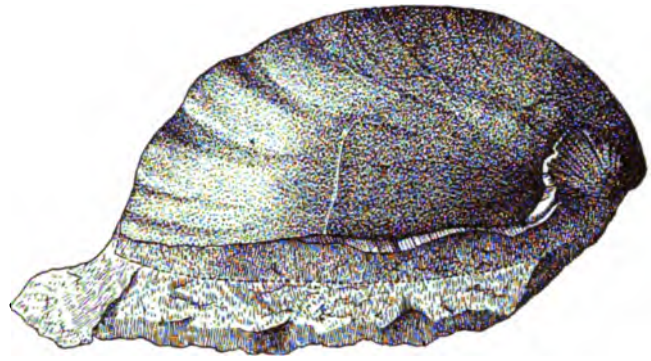
The group as a whole.—Briefly summarizing the characters of these three formations, one may say that the Benton group has a total thickness of 400 to 450 feet. It is a body of gray shale, divided midway by a limestone formation, and including at top a thin, purplish limestone or a thicker yellow sandstone. Its thickness at all points of measurement is so nearly the same that great dependence can be placed upon it in estimating at various localities the distance which must be traversed by the drill to reach the water-bearing Dakota sandstones below.

NIOBRARA GROUP.

The formations of this group are chiefly of shale, but the members of it which are most frequently exposed to view, and thus attract attention, are limestones. Its entire thickness has been measured at a few points only, being there found to be about 700 feet, but rough approximations in other localities give the impression that its thickness is nearly uniform.

Timpas formation.—The lower members of the Niobrara group are collectively called the Timpas formation. The general thickness of the Timpas is 175 feet, and it may be characterized as a series of limestones and calcareous shales with prevailing pale colors.

At base is a limestone series about 50 feet thick. The individual beds range in thickness from a few inches to 3 feet, the average being about 1 foot. They are separated by layers of gray shale, usually 1 or 2 inches thick. The limestone has a light gray color, which becomes creamy white on weathered surfaces. It is compact and rather fine grained, and where exposed to the weather breaks up into rough flakes, of which the longer dimensions are parallel to the bedding. This peculiarity ordinarily serves to distinguish it from the Greenhorn limestone, which cleaves into vertical plates. Near the eastern edge of the district its texture is somewhat coarser, its color is paler, and the fractured surface resembles chalk. Still farther east, especially in Iowa, the rock acquires all the characters of a true chalk. In its lower layers are small nodules of iron sulphide, which are converted by the chemical reaction of the air to limonite. As the limestone is broken up and removed by the action of the weather, the more resistant nodules are freed from their matrix so as to lie loose on the surface. They are of a dark-brown color and of oval or cylindrical form, with a diameter of about half an inch. Their surfaces are not even, but are set with angular projections, the ends of crystals (Pl. LIX). The characteristic fossil of the limestone is a thick bivalve shell (*Inoceramus deformis*), the outer surface of which is usually covered by the shells of a small oyster (*Ostrea congesta*). The shell itself can rarely be found free from its matrix, but a limestone cast having the form of its interior is frequently seen, and can always be discovered by a little search where



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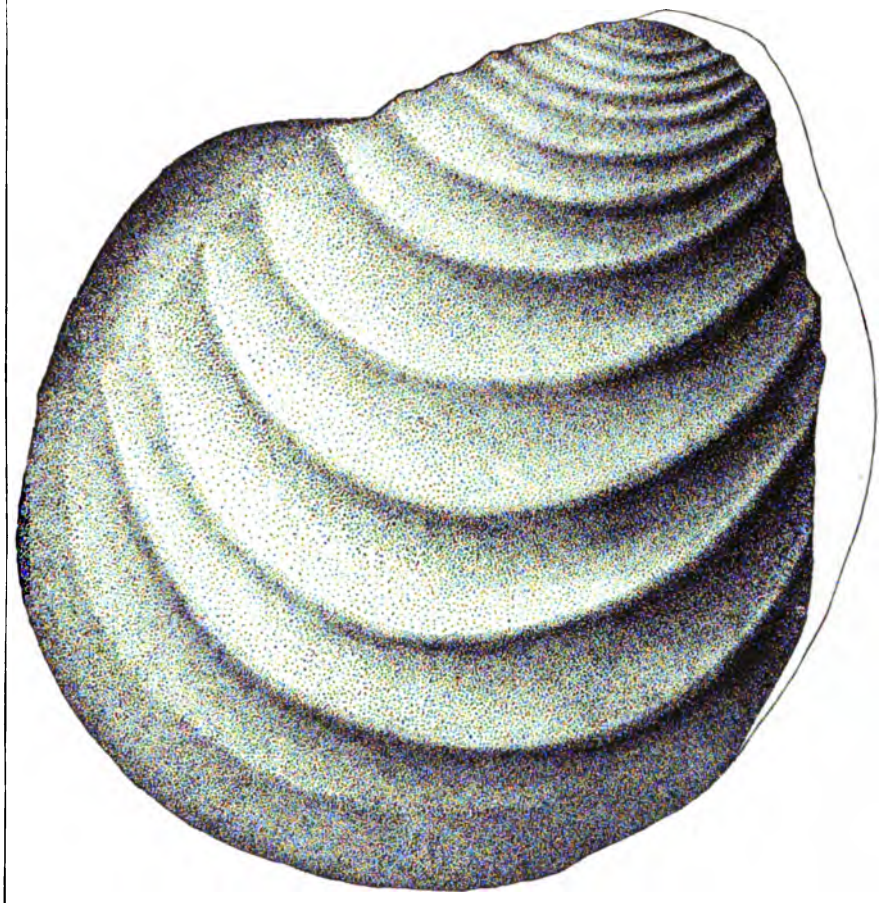

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INOCERAMUS DEFORMIS, A FOSSIL BIVALVE SHELL FOUND AT MANY LOCALITIES IN THE TIMPAS LIMESTONE. THE TWO VALVES ARE USUALLY SEPARATED.

Fig. 1. The edge of a small individual.
Fig. 2. The side of an individual of moderate size.

The mud which once filled the shell was hardened into stone and the shell was afterwards broken away, so that the illustration represents casts of the interiors of the shells. In Fig. 1 a small portion of the shell remains.

A GROUP OF OYSTERS, OSTREA CONGESTA, ATTACHED TO A FRAGMENT OF INOCERAMUS SHELL.

Such groups are found in several formations, but they are peculiarly abundant in the upper part of the Timpas formation.

the rock is quarried or is worn by a stream. Its form is suggestive of the hoof of a horse (Pl. LX).

The upper limit of the limestone is indefinite. It passes gradually into a light-gray, limy shale, which contains occasional thin beds of limestone and has a total thickness of 100 or 125 feet, terminating at top in one or two layers of chalky limestone containing several species of fossil shells and also the remains of fishes. The most abundant shell is a very broad, flat bivalve belonging to the genus Inoceramus, and usually covered by *Ostrea congesta*. The shell of Inoceramus has a fibrous structure at right angles to the surface, causing it to break easily, and the individuals of this species are always broken into many pieces, so that the specimens actually found are fragments of plate-like shells with oysters attached to one side (Pl. LXI).

Apishapa formation.—The upper part of the Niobrara group constitutes the Apishapa formation. It is chiefly an argillaceous, laminated shale, of dark-gray color, but it is modified by atmospheric action to a considerable depth, acquiring a yellowish color and rougher texture. Gypsum in thin plates is somewhat abundant, and in unweathered specimens a short search will always discover oval fish scales from one-third of an inch to an inch in diameter. At top a few layers contain so much lime as to constitute an impure limestone, and they have been quarried at some points, especially at Pueblo, for foundation stones, etc. They contain fish scales and a few fish bones. At various horizons, especially in the eastern part of the district, are calcareous concretions, usually of considerable size. They are never spherical, like those of the Carlile formation, but are broadly ellipsoidal, and at a few points they coalesce with one another so as to form a continuous bed several rods in extent. Below the middle of the formation a series of these concretions have internal cracks similar to those of the concretions found in the Carlile formation, but containing, in addition to calcite, large crystals of barite, or heavy spar, a translucent mineral with faint-bluish color, which may be distinguished from calcite by its greater weight. At points south and west of Fowler barite has been collected by mineralogists for exhibition in museums. The entire thickness of the formation is approximately 500 feet.

PIERRE GROUP.

Above the Niobrara group is a great deposit of laminated, argillaceous shales, not interrupted by sandstone, limestone, or other hard layers. In the vicinity of Florence, where the whole of the group is seen, its thickness has been estimated as more than 4,000 feet.[1] In other parts of the district only the lower part of the group occurs, and it is probable that the thickness does not exceed 2,500 feet. There are considerable variations in color, texture, and contents, from bottom to top of

[1] The Florence oil field, Colorado, by George H. Eldridge: Trans. Am. Inst. Min. Eng., Vol. XX, 1891, pp. 442-462.

the series, and by their aid several zones have been recognized, but none of these are sharply limited, and it has not been practicable to distinguish definite formations.

The lower part, for a depth of 400 or 500 feet, is of medium-gray color and has a certain roughness of texture due to minute flakes of selenite, the crystalline form of gypsum. It is practically barren of fossils, for, though their presence can be detected by careful search, they are rarely so well preserved that they can be collected. It contains so few concretions that their scarcity serves to distinguish it from the next zone, where they are abundant.

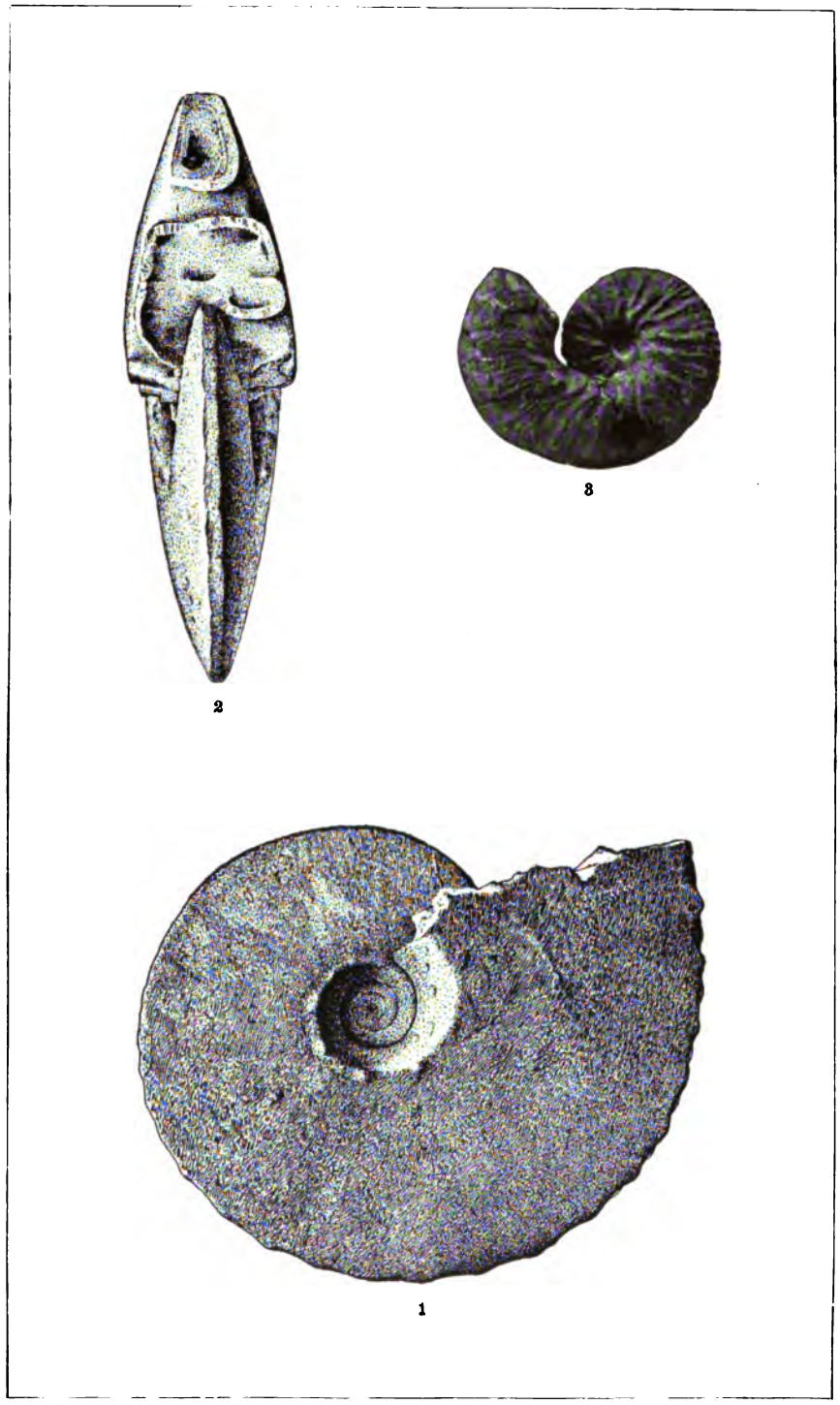
Above the barren zone is a zone of similar color, but with less selenite, characterized by a great abundance of ovoid concretions, ordinarily from 4 to 8 inches thick and two or three times as broad. These are dark gray on surfaces of fresh fracture, fine textured, and tough. They consist of carbonate of lime and carbonate of iron. At certain horizons they contain fossils, but these are not a conspicuous feature. Under the action of the weather they break up into angular fragments a fraction of an inch in diameter, which have the color of iron rust; and on bare slopes these fragments occupy so much of the surface as to give it a reddish-brown color. The thickness is approximately 600 feet.

Beginning in the lower, or Rusty, zone, and extending upward for 100 or 200 feet, where the shale becomes paler, is a zone characterized by the abundance of a peculiar fossil, *Baculites compressus*. This is a relative of the nautilus, but its shell, instead of being coiled like those of the nautilus and snail, is straight. It has the form of a flattened cylinder, tapering slightly from one end toward the other. Many of the fossils are of dull-gray color and stony texture, but others are white or pearl-gray and retain the pearly luster of the living shells. They are not confined to this horizon, but are more abundant here than above or below. The largest individuals occur somewhat higher, and it is one of these that is pictured in Pl. LXII.

The Tepee zone, though grading insensibly into the zones above and below, has characteristics which are somewhat striking. Its thickness is estimated at 1,000 feet. The shale is of fine texture and medium-gray color. Concretions are rather abundant, and larger, on the average, than in the Rusty zone. They ordinarily range in thickness from 6 to 12 inches and are several feet in horizontal extent. As in the other zones, they occur along certain lines or levels instead of being scattered irregularly through the shale. In them are preserved fossils of great beauty and often of considerable size. Among these are a large baculite, frequently 2 or 3 inches in diameter (Pl. LXII), and several coiled shells related to the ammonite (Pls. LXIII, LXIV, and LXV). A large, smooth bivalve, *Inoceramus sagensis*, ranges from 4 or 5 inches to a foot in diameter (Pl. LXVI, fig. 2). All these shells, when freshly broken from the concretions, are white and retain the pearly luster; but where acted on by the weather they have either the dull gray of the concretions or the yellow of iron rust.

BACULITES COMPRESSUS. SIDE VIEW OF A LARGE INDIVIDUAL.

The oval diagram shows the form of the cross section. Individuals of this size are found in the Tepee zone of the Pierre shale. Smaller individuals are more abundant in the Baculite zone.



PLACENTICERAS PLACENTA AND SCAPHITES NODOSUS.

These fossil shells are found at many localities in the Tepee zone of the Pierre shale, and *Scaphites nodosus* occurs also in the limestone cores of the Tepee Buttes.

Figs. 1 and 2 give side and edge views of a small Placenticeras. Specimens often have a diameter several times as great.

Fig. 3. A small variety of *Scaphites nodosus*.

The zone is further characterized by what have been called "Tepee cores." These are masses of coarse-textured, gray, fossiliferous limestone, irregular or rudely cylindrical in form, and standing vertical within the shale mass. Ordinarily they are from 5 to 30 feet in horizontal diameter, and their vertical extent is greater. As the wash of rains carries away the shale, these cores, being more resistant, are left projecting from the surface, but they do not stand as columns. Fragments broken from the top by frost fall on the adjacent shale and protect part of it from the rain, so that the position of each core is marked by a conical hill of shale, with the limestone projecting slightly at top. These little hills (Pl. LXVII) have been called "Tepee buttes," on account of their resemblance to the tepees or lodges of the Shoshone and other Indians. The fossils in the limestone are of great variety, including all kinds that occur in the surrounding concretions, but the most abundant species is a bivalve shell, about an inch in width *Lucina occidentalis* (Pl. LXVI, fig. 1). It is possible that these cores do not everywhere characterize the shale at this horizon, but they have been found at various points from Canyon to Cow Spring.

Above the Tepee zone the shales are comparatively, though not absolutely, barren of fossils. Their color is in general darker; selenite is somewhat abundant; concretions are less abundant, and at a number of horizons are thin, discontinuous, limy layers with cone-in-cone structure. There are also fillets of structureless white clay similar to that occurring in the Carlile formation.

Measured from the base of the group the middle of the Rusty zone has a height of about 800 feet, the middle of the Baculite zone 1,200 feet, and the middle of the Tepee zone 1,700 feet.

FOX HILLS GROUP.

The Fox Hills group is composed chiefly of sandy shale, which grades downward into the argillaceous shale of the underlying Pierre and upward into a yellow sandstone. Within the district it occurs only in a small tract near Florence, where its thickness is reported by Eldridge as 450 feet. Lying 5,000 feet above the water-bearing Dakota sandstones, it is not traversed by artesian wells, and its characters need not be further described in this place.[1]

[1] For the benefit of the reader who may have occasion to consult other works treating of the geology of the Great Plains, it is proper to state that the groups here enumerated do not comprise the whole of the Cretaceous system of the plains, and also that various other designations are in use for some of the strata here included. The first classification of the Cretaceous of the plains was by F. B. Meek and F. V. Hayden, who gave the names:

5. Fox Hills.
4. Fort Pierre.
3. Niobrara.
2. Fort Benton.
1. Dakota.

The Laramie formation, which in some regions overlies the Fox Hills, is now classed with the Cretaceous, and the Comanche series, which has great development in Texas, has been recognized as of Cretaceous age and older than the Dakota. It is possible that some of the beds here classed as Juratrias may eventually be correlated with the Comanche. In the reports of the Fortieth Parallel Survey,

RÉSUMÉ OF THE CRETACEOUS FORMATIONS.

In their more general features the Cretaceous formations constitute a simple system. At base are a few hundred feet of sandstones with interbedded shales; above are several thousand feet of shale, varied somewhat in texture and color, interrupted here and there by beds of limestone, and characterized at various horizons by peculiar fossils and peculiar concretions. These general facts are represented in fig. 46, which is drawn to scale so as to show the relative thicknesses of the principal component beds. The undulating lines of the Dakota group indicate the varying thickness and distribution of the Dakota sandstones. The straight lines above represent the comparative uniformity of all the other formations. The tepee cores are shown by vertical lines. One margin of the diagram is shaped to indicate relations of hardness, the harder beds being made to project beyond the softer, as they sometimes do on the face of a cliff. The Fox Hills group and the upper part of the Pierre are omitted as unimportant with reference to problems of water supply.

While it is probable that all these formations once extended over the whole district, the present condition is very different. They have been worn away unevenly, so that over certain areas the Pierre shales are shown at the surface, over other areas the Niobrara formations, over others the Benton, and over others the Dakota. Wherever any of the higher formations occupies the surface there is reason to believe that the Dakota lies beneath and can be reached by boring. Moreover, the general facts in regard to thickness enable anyone who has determined which formation constitutes the surface at any point to predict, with fair approximation, the depth to which it would be necessary to drill in order to reach the water-bearing strata of the Dakota. When the detailed work of the United States Geological Survey has been completed in the district its maps will record such information with considerable precision; but the inquirer need not wait for that final work if

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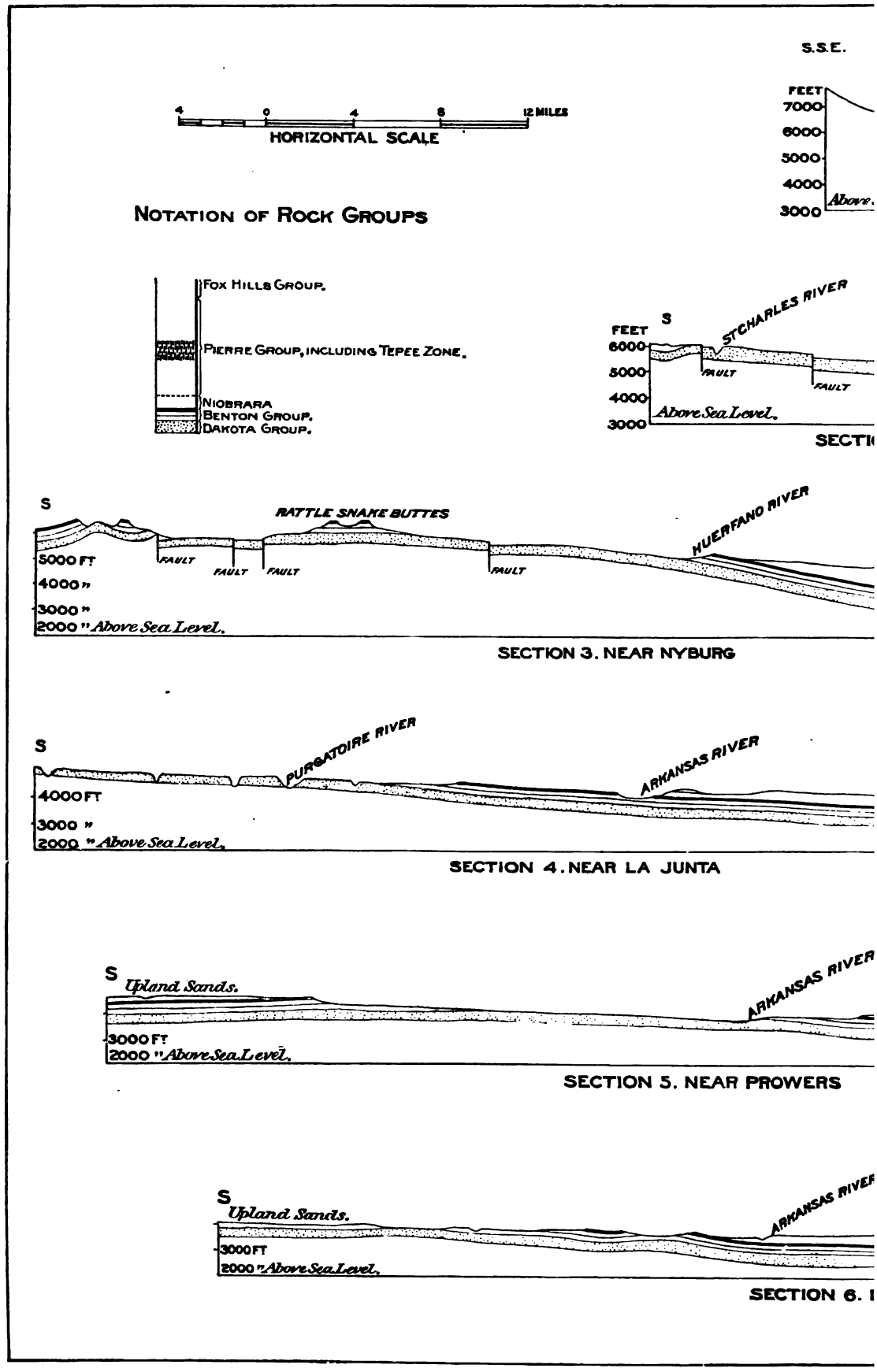
the Fort Benton, Niobrara, and Pierre are classed together under the name Colorado Group. C. A. White, in 1878, classed together the Fort Benton and Niobrara under the name Colorado, and the Fort Pierre and Fox Hills under the name Fox Hills. This usage was followed by various writers. In 1889 Mr. George H. Eldridge proposed "Montana" as a generic term including the Fort Pierre and Fox Hills, retaining "Colorado" as a generic term for Fort Benton and Niobrara. For the purposes of the present paper the more inclusive terms have not been required, but, on the contrary, it has seemed desirable to subdivide the Benton, Niobrara, and Pierre groups.

The names applied by the writer to formations and zones within those groups are here published for the first time. The Graneros shale is so named from a creek in longitude 104° 47′, latitude 37° 57′, where the formation is well exhibited. The title was suggested by Mr. R. C. Hills. The Greenhorn limestone takes its name from Greenhorn station, 14 miles south of Pueblo, and from Greenhorn Creek. The Carlile shale is named from Carlile Spring and Carlile station, 21 miles west of Pueblo. The Timpas formation is named from Timpas Creek, which enters the Arkansas below Rocky Ford. The Apishapa formation is named from Apishapa River, which reaches the Arkansas near Fowler.

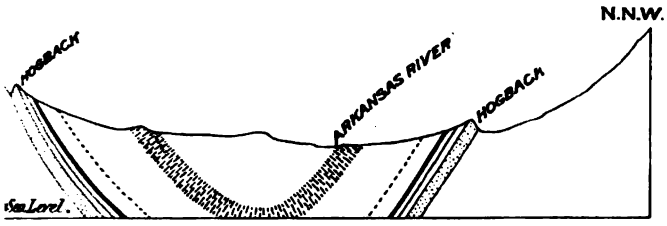
In a report on the fossils of the Colorado Group (Bull. U. S. Geol. Survey No. 106), Mr. T. W. Stanton gives the title "Pugnellus" to the sandstone and equivalent purplish limestone at the top of the Carlile shale; but it has not seemed advantageous to follow him in the present report, as the fossil shell, Pugnellus, which he found characteristic in another district, is of rare occurrence in the region here described.

HETEROCERAS NEBRASCENSE. Natural size.

The perfect individual has several coils like those at the top of the figure and a single open coil at the bottom, as in this instance, but the shell is usually found in fragments a few inches in length. It is characteristic of the Tepee zone of the Pierre shale.



SECTIONS ACROSS THE ARKANSAS VALLEY FROM SOUTH TO NORTI



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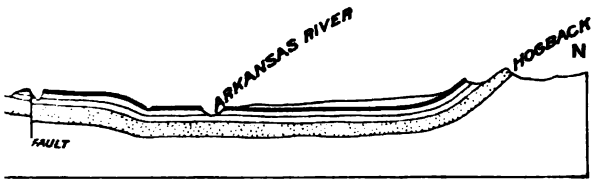
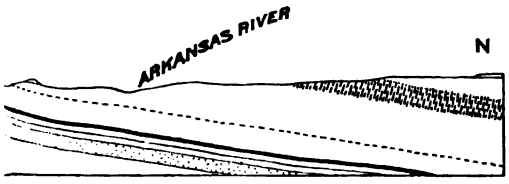
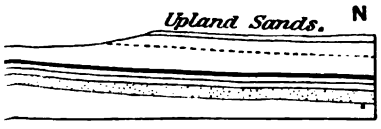
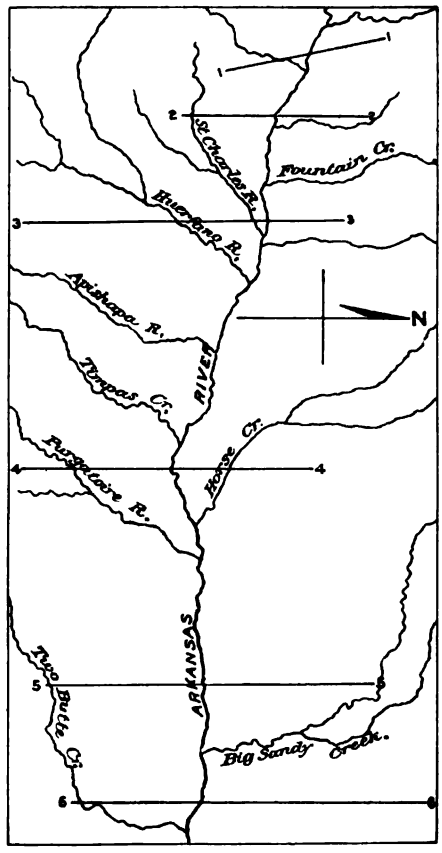


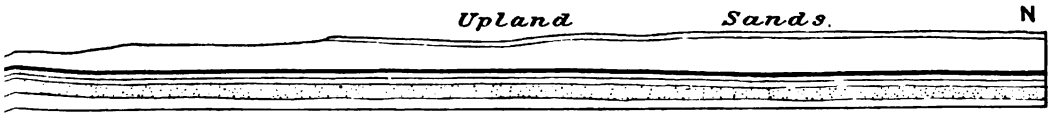
ION 2. WEST OF TURKEY CREEK







SKETCH MAP SHOWING RELATIONS OF SECTIONS



NEAR GRANADA

SHOWING THE ARRANGEMENT OF THE CRETACEOUS ROCKS

The bending and faulting of the Cretaceous rocks and the general uplift which inclined them toward the east and north took place long ago. From the moment of the emergence of the rocks above the sea they were attacked by eroding agents. By alternate wetting and drying, freezing and thawing, the coherent particles near the surface were loosened. Rains washed them to stream channels, and the streams carried them to the distant sea, and thus the surface of the land was worn away. It is not difficult to understand this process, for a little observation will show that it is now in progress in the same region. If one digs down a few feet or a few yards into the Cretaceous shales, he finds them quite compact; but at the surface, where shower and frost have acted, they are reduced to an incoherent earth. Whenever a storm comes some of this earth is washed away from the land and carried by the creeks to the Arkansas River, the Arkansas delivers it to the Mississippi, and the Mississippi to the ocean. The mud in the river water is the waste of the land in process of transportation.

It is evident that however rapid this process may be, or however long the time during which it is continued, the land can not be worn down below the level of the ocean. Geologists express this law by saying that the ocean is the "base level of erosion." Moreover, as streams run slowly where their beds are inclined gently, and with comparative swiftness where their beds are steep, and as mud and sand constantly settle out of slow-running water, erosion can not progress rapidly unless the river channel and the stream channels have a certain amount of slope. When the degradation of the country has gone so far that all the slopes are gentle, its progress is comparatively slow. The tendency, therefore, is to reduce the whole region to a system of shallow valleys with gently sloping sides, traversed by streams whose beds incline toward the great trunk line of transportation, the Mississippi. It was probably reduced to this condition in the period of erosion just mentioned as following the uplift and disturbance of the Cretaceous rocks. We may think of the surface of the Great Plains as then more nearly level than it is now.

Eventually the process of erosion was completely arrested, and processes of deposition took its place. This change was brought about by some modification of conditions which is not yet clearly understood. Perhaps the plains region was depressed at the west, and the slopes thus rendered so gentle that the streams could no longer carry off the detritus which came from the mountains, and it was deposited on the way. Perhaps a barrier was lifted at the east, so that the base level stood higher. Whatever the cause, the streams which flowed from the mountains onto the plains, and thence eastward across the plains, ceased to carve valleys in the region of the plains and began to deposit sediment. When they had filled their channels so that their beds lay higher than the neighboring country, they broke through their banks, shifting their courses to new positions, and they thus came to flow in succession over all parts of the plains and to distribute their deposit

widely, so that the whole plain in the district here described was covered by sands and gravels brought from the canyons and valleys of the Rocky Mountains. It is thought by geologists who have studied the formations of Kansas that lakes were formed there during a portion or the whole of this period, so that the sedimentation was from still water instead of from the currents of sluggish streams. It is probable that during part of the period such lakes extended into northeastern Colorado, but the principal work within the field of our reconnoissance appears to have been done by running water. In a general way, the deposits seem to have been heavier toward the northeast than toward the south and west, but the difference was not great. The range in observed thickness is from 50 to 200 feet.

The chief material is coarse sand, and this is arranged in irregular beds with much oblique lamination, such as ordinarily results from the work of streams. In the sand are occasional pebbles, and these are in places gathered into distinct beds of gravel. Except near the base of the formation the pebbles do not include fragments of the Cretaceous rocks of the plains, but are of harder materials, able to survive the wear and tear of a long journey. North of the Arkansas River they seem to have come wholly from the Rocky Mountains, and they resemble the material now brought by Fountain Creek from the vicinity of Pikes Peak. South of the Arkansas they include also certain volcanic rocks which occur in the Spanish Peaks and neighboring mesas.

Where the sand rests on the Cretaceous rocks it is often bound together with a limy cement, so as to constitute a sandstone, but this phase has usually a thickness of only 1 or 2 feet. At several places on the north side of the valley zones of cementation were seen at higher levels, the calcareous cement being so abundant as to close all interstices, converting the sand into a calcareous sandstone, or sometimes into a sandy limestone. At the northeast, in the valleys of various creeks tributary to the Smoky Hill River, clays, marls, and other fine-grained beds alternate with the sand in the lower part of the formation, and these are probably continuations of the lake deposits observed in Kansas.

Near the top of the sand are occasionally found thin, broad, lens-shaped bodies of a fine earth called "loess," and the same material overlies the sand at many places. Loess is a peculiar material, and its origin is often doubtful; in some instances it has been ascribed to the action of the wind, in others it has been referred to deposition in still water. It may be that the deposits of this region have been formed partly in the one way, partly in the other, but the chief agent appears to have been wind. The dust raised by violent windstorms, such as are familiar to the residents of the district at the present time, must somewhere descend to the earth, and if it falls on land occupied by vegetation the wind does not again lift it. The soil thus formed has an open texture, so that it absorbs most of the rain falling upon it, and is thus protected from the washing effect of rain water running over the surface.

So by streams, lakes, and winds there was spread a great mantle of sand and silt, by which the minor valleys and hills were buried from sight and the Cretaceous formations were at the same time concealed.

Eventually deposition was in turn arrested and erosion resumed. The streams, which had been shifted from one course to another so as to occupy successively and many times each part of the surface, became fixed in position as soon as changing conditions caused their waters to erode once more. The cause of the new change was probably renewed uplift—a general elevation of the plains region, which was greater at the west than at the east, so that the eastward slopes were increased. Streams flowing in that direction acquired a greater velocity, and were able not only to carry forward all the detritus with which the storms fed them, but also to wear their beds and deepen their channels. As the stream channels were worn slowly down the earth of adjacent slopes was washed into them, and thus broad valleys were opened out. Then from the uplands between the valleys more or less of the sandy formation was washed down, so as to form a coating over the slopes of the valley. As the material occupying the slopes is identical in character with the great deposit whence it was derived, it is now hard to distinguish them, and the name "upland sands and gravels" is applied alike to the original and the derivative deposits.

At a later epoch the land was lifted still higher and erosion greatly accelerated, so that the stream valleys were deepened several hundred feet without being opened so broadly as before. This later action gave somewhat definite limits to the upland formation, which now constitutes a high plain or plateau, separated from the greater stream valleys by a line of bluffs, and along this bluff line the Cretaceous formations are usually to be seen in contact with the overlying sand.

On the northern slope of the Arkansas Valley the upland sands approach the river within 5 to 15 miles, their limit being marked by bluffs from Pueblo to the Kansas boundary. The bluff line is broken only by the valleys of tributary streams. The reports of other geologists indicate that the formation extends northward for many miles, but from personal observation the writer can only say that it passes everywhere beyond the field of his reconnoissance.

On the southern slope of the valley the formation lies much farther back from the river, having been seen only in the southern part of Prowers County, at distances of 12 to 15 miles, and at a somewhat greater distance in the southern corner of Bents County. Thence it extends to an unknown distance southward, and the study of topographic maps indicates that it also extends toward the southwest in Las Animas County.

TERRACE SANDS AND GRAVELS.

The broad valley dug by the Arkansas and its tributaries since the spreading and respreading of the upland sands and gravels has a depth of from 400 to 800 feet. Its sloping sides are composed chiefly of the

shales and other rocks of the Cretaceous system, but there are many local belts of gravel and sand. Except where the sand has been disturbed by the wind, these belts are flatter than the neighboring slopes, and they are usually sharply limited toward the river by steep slopes or bluffs so as to constitute benches or terraces. Much of the irrigated land of the valley lies on these terraces. In some cases the gravel and sand are covered by a few feet of loam, and their presence is then discovered only through wells or by an examination of the terrace at its margins.

These terraces were all made by the river and its branches during the progress of the excavation of the valley, and it is easy to understand them if one notes the present condition and habits of the river. The river is a great carrier of mud, sand, and gravel. This work it performs chiefly at time of flood, and the finer part of its load can then be seen in the water as the torrent rolls along. The gravel can not be seen in motion as it is dragged and rolled along the bottom in the deeper parts of the channel, but its presence may be noted here and there at low stage.

On the outside of each curve of its course the torrent digs into the

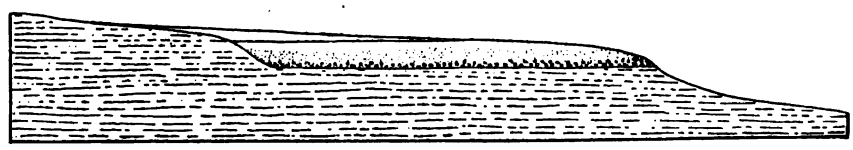


FIG. 47.—Diagrammatic section across a terrace. The dots show sand and gravel, the broken lines bed rock.

bank, so that the river encroaches on the land; but the channel does not grow broader, because in the quieter water on the inside of the curve some of the sand settles from the water, and new land is thus built up. At first the accumulating sand makes only a shoal, but as the main current works farther and farther away, sand and mud are gradually added until the level of the bottom land, or flood plain, is reached. In fact, the whole flood plain of the river has been formed in this way. Some of the bends lie wholly in the flood plain, so that what they dig out is merely alluvium that the river had previously deposited; other bends touch bed rock, and by digging in that make the flood plain broader.

As the stream thus gradually shifts its channel all over its flood plain, it leaves behind an assorted deposit. The lowest layer is gravel, and this rests directly on the Cretaceous bed rock; then comes sand, and, above the sand, clay or loam.

Each of the terraces of the valley slopes is part of a river flood plain, formed when the valley had been dug only to that level. The oldest are those lying highest, and the newest of all is so near the modern flood plain that it is called the "second bottom." As a result of this

origin the terraces have the general structure indicated in the diagram (fig. 47). Ordinarily the thickness of the deposit is not greater than the maximum depth of the river during high water. The newer terraces have loam, sand, and gravel. The older have often lost the loam and sand, especially near their bluff edges, and retain only the gravel. In a few cases the thickness of the deposit is greater than the high-water depth of the river, showing that the digging of the valley was interrupted by short periods of valley filling.

Most of the terraces have a gentle grade toward the river, the outer part having been somewhat washed away by rain and the inner part built up by material washed from higher slopes. They have also a gentle grade eastward parallel to the river, and this grade was given to them chiefly in the process of their formation. It is possible, however, that part of it has been caused by a slow rising of the western part of the plains. An attempt has been made to identify each of the stronger-marked terraces from point to point, so as to learn its original extent and position, and this investigation has shown that they descend eastward more rapidly than the present grade of the river.

While the Arkansas was making its valley, each tributary river was engaged in a similar work, and similar systems of terraces record the stages of its progress. At river junctions the terraces of two valleys are frequently seen to unite.

DUNE SANDS.

Yet another geologic formation deserves mention in this place by reason of its relation to water supply. When the wind blows over a bed of dry sand that is not protected by vegetation, grains of sand are drifted along over the ground. Any little obstruction, by checking the wind, tends to stop them, and when they have once begun to accumulate at any point their own heap acts as an obstruction, creating behind it an eddy of the wind, where the grains more rapidly lodge. On the windward side of the hill the wind is a little accelerated, so that there is a tendency toward excavation. By excavation on the windward side and accumulation on the lee side the hill of sand slowly travels in the direction of the wind's motion. Such traveling hills are called dunes.

On the broad plains underlain by the upland sands and gravels there are a number of local districts where the sand is fine enough to be moved by the wind and the vegetation is too scant to hold it. It is there blown about and gathered into dunes. If the wind blew as frequently and as strongly from one direction as another, the hills would make no progress; but all through the district the prevailing winds are from the northwest, and the sand hills therefore travel toward the southeast. The most important district of this class occupies a portion of the northern slope of the valley, having its southwestern limit near Carpenter Spring and the Langford ranch, its southeastern near Ante-

lope Springs, and extending thence northward. The whole surface of this district, so far as explored, is a system of hills and hollows without drainage by streams, so that all the rain which falls on it and is not evaporated from the surface is absorbed by the sand. There are a few localities where the terrace sands have been disturbed by the wind, but they are comparatively unimportant and need not here be described.

Another source of dune sands is found in stream beds. Nearly all the streams of the district carry sand along their beds and build it into flood plains. Sometimes the sand is combined with so much clay that after it has become dry the grains stick together; but in other instances the streams carry little clay, and the sand, after drying, is quite loose. Under such circumstances the parts of the stream beds laid bare at low water, being without vegetation, are subject to the attacks of the wind. The sand is blown on the banks and built into dunes, and the dunes move slowly across the country. Two streams of the northern slope give rise in this way to broad belts of dunes. Black Squirrel Creek, the principal branch of Chico Creek, rising among the upland sands, carries their material southward and yields it to the wind at various points. The belt of dunes thus created blends in part with the broad tract of dunes just mentioned to the northwest of the Langford ranch. Big Sandy Creek and its principal tributaries similarly head in the upland sands and flow southward, and the immense body of sand carried by them furnishes to the wind the material for a broad belt of dunes following their eastern banks. In a similar way the sands brought by the Arkansas River are built into dunes along its south bank from La Junta eastward. The general course of the river is there from west to east, and as the prevailing wind blows toward the southeast the sand moving from the river bed in that direction, rises over the southern bank. The belt of dunes thus created is crossed every few miles by a stream running northeastward to join the Arkansas. None of these streams are perennial. The larger of them flow several months in each year, and all flow during periods of exceptional storm. As the sand is blown into their beds it tends to clog them, but the storm waters clear out the channels and carry the sand back to the Arkansas. Thus there is a perpetual conflict between the winds carrying the sand southeastward and the streams carrying it northeastward. As a result of this conflict, the sand belt, which would doubtless otherwise be much more extensive, is limited to a breadth of 3 or 4 miles.

ARTESIAN WATER.

Underground water falls into two general classes. It may flow through a porous bed which is continuous to the surface of the ground, in which case the position of its upper surface varies with the supply; or it may flow through a porous stratum confined between impervious strata, in which case it usually occupies the entire stratum

and presses, not only downward on the limiting impervious rock beneath, but upward against the impervious cover. When water of the first class is reached by a well it retains its natural level within the well. When a well is put down to water of the second class the water rises somewhat within the opening, the height to which it rises being determined by its original pressure against the covering rock. If the conditions are favorable it may rise to the surface of the ground and flow out. Water which does not rise in the well is called "ground water." For the class of underground waters which do rise usage is divided. By some writers all such waters are called "artesian;" by others the term is limited to such waters as have sufficient head to outflow at the surface. It will be convenient in this paper to conform to the first-mentioned usage, defining artesian water as that which presses upward as well as downward on the walls of its conduit, so as to rise toward the surface, or perhaps above the surface, when a way for it is opened. The wells which draw water from such a source are ordinarily described as "flowing" when the water is naturally discharged at the surface, and as "pumping" when the head is not sufficient for a natural discharge.

GENERAL CONDITIONS.

That underground water may be artesian, two things are essential: First, that the porous bed receive its supply at a point or in a region where it lies comparatively high; second, that it be inclosed by comparatively impervious beds. If the inclosing beds permit no water to escape, and completely surround the reservoir except in the region of supply, then wherever the reservoir is tapped by a boring the water will rise to the height of the lowest point of supply. This ideal condition is never realized. The rocks called impervious are not absolutely water-tight, but only relatively so; and few water-bearing rocks are completely inclosed by rocks of the impervious class. The head of artesian water is therefore somewhat lower than the region of supply, and it may be much lower.

Usually there is a slow but continuous movement of water through pervious strata from the district of supply downward to points of natural discharge; and the pressure on the covering rocks is largely regulated by variations in the resistance to the water's movement, depending on the texture and thickness of the porous bed. In places where the bed is relatively thin or its texture relatively fine the resistance to flow is relatively great, and this resistance operates to increase the head at points nearer the source.

The practical value of a body of artesian water also depends on the quantity which can be continuously supplied to wells, and this, in turn, on the size and character of the conduit, on the freedom with which water is received in the region of imbibition, and in some cases on the rainfall. The value depends in part also on the quality of the water, on its depth beneath the surface, and on various other factors affecting

the cost of securing it. The natural circumstances affecting the availability of artesian water are ably and comprehensively treated in the Fifth Annual Report of the United States Geological Survey, in a paper on "The requisite and qualifying conditions of artesian wells," by Thomas C. Chamberlin.

WATER OF THE DAKOTA SANDSTONE.

In the district under consideration the only artesian water of demonstrated value is that contained in the Dakota sandstone. It is probable that there is no other formation from which water can be profitably obtained, and it may be asserted with confidence that no other compares in importance with the Dakota sandstone.

GATHERING GROUNDS.

The water is received by the Dakota sandstone in the region where that rock outcrops at the surface, and also in the region where it is covered only by the upland sands. The regions of outcrop which may be supposed to affect the supply in this district comprise, first, the line of so-called hogbacks; second, a number of broad outlying tracts at various points on the plains. The hogbacks are a chain of high ridges, overlooking the plains and separated from the mountains by a chain of valleys and parks. From Colorado Springs they run southward to the canyon of Turkey Creek, then westward past Glendale to a point just north of Canyon, and southward and southeastward to a point a few miles northeast of Beulah, where they turn southward to the Three R ranch. They are there interrupted, but reappear in a few miles and continue along the base of Greenhorn Mountain and beyond. In some places the chain includes several parallel ridges, elsewhere but one. The chief ridge is everywhere definitely associated with the Dakota sandstone, and marks the place where the sandstone is turned up at the foot of the mountains. The relation of the sandstone to the hogbacks is illustrated by fig. 48, and also by sections 1 and 2 of Pl. LXVIII.

In the figure the Dakota sandstone is represented by a broad line ending in the hogback H, and the lower slopes of the Wet Mountains appear at W. Here, as elsewhere, the sandstone ridge is separated from the mountains by a valley, so that the sandstone does not receive the water of mountain storms and snow banks, but only that which falls on the narrow ridge. At this particular point the sandstone belt, from H to I, is about a mile broad; from I to T the formation is covered by the Benton shales, and from T to S by the Timpas limestone, except where divided by the Arkansas canyon, A. At some points the width of exposed sandstone is greater, but generally it is less, and the average is not more than a mile. Where it is narrow, the slopes are so steep that a large share of the storm water runs off and the sandstone can imbibe but little; but the broader parts of the belt have gentler slopes, more or less covered by a blanket of sand, in which the rain water is

stored for a time, and from which it may be slowly absorbed by the sandstone.

The most westerly of the outlying areas lies just outside the hogbacks in the region drained by the head waters of Peck Creek and Rock Creek and traversed by the main branch of the St. Charles River. It has an area of 50 or 60 square miles. Another district begins about 20 miles south of Pueblo, includes nearly the whole of the Virgil and St. Vrains grant, and extends thence southward and southeastward. Its extent is approximately 500 square miles, and the slopes are sufficiently gentle to make the conditions for absorption favorable. A third tract of importance has its northern margin at the Arkansas River between Las Animas and the mouth of Mud Creek, and extends thence to the south and southeast. It borders the Purgatoire River on both sides to Bents Canyon and beyond, and includes large areas drained by Blue, Caddoa, Mud, and Clay creeks. Its extent is not fully known, but the total area is not less than 1,000 square miles. Contiguous to this is a district of unknown extent in which the Dakota sandstone is covered by the upland sands, from which it may receive water. Beginning at the

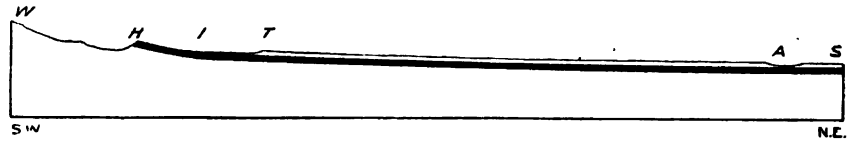


FIG. 48.—Section from the Wet Mountains to the Arkansas River, along a line west of Red Creek, showing the relation of the Dakota sandstone to the surface of the country. Scale, about 4 miles to the inch.

head waters of Clay and Wolf creeks, the district extends southward and southeastward across Two Butte Creek and probably to the basin of Horse Creek.

It is impossible to say what share of these areas contributes water to the sandstone. In part they are occupied by the upper layers of sandstone, which are so fine textured as to receive little water. The irregularity of the sandstone beds is so great as to raise the question whether all of the porous beds exposed to the rain are of such horizontal extent as to carry water to the deeply buried portions of the formation. Such considerations make it impossible to estimate the amount of water which may annually be imbibed, and for the present at least it is useless to discuss the annual rainfall with reference to the extent of the gathering grounds.

CAPACITY.

Whether we regard the Dakota formation as a reservoir containing a body of water from which a supply may be drawn by wells, or as a conduit through which water is flowing, its capacity depends on the thickness of the water-bearing sandstone strata and on their porosity. Some experiments conducted by Mr. G. W. Stose, of the Geological Survey, indicate that the beds of more open texture are able to absorb

18 per cent of their volume of water.[1] In the western portion of the district the thickness of rocks having approximately this capacity is estimated at from 150 to 175 feet; farther east it is considerably less, but in the gathering grounds at the south, where the rocks are exposed to direct examination, it is probably nowhere less than 75 feet. Taking the smallest figure as a limit and applying the factor of porosity, we find it probable that all portions of the district in which the sandstone constitutes a deep-lying formation have beneath them at least 12 cubic feet of artesian water for each square foot of surface. This statement views the Dakota sandstone as a reservoir, and has no direct bearing on the quantity that can be obtained from the rock at any point except that it affords a guaranty of practical permanence to any supply which may be derived.

The amount of water flowing from a well depends in part on the height of the point of discharge as compared to the head of the water, or the pressure which it naturally exerts on the overlying impervious rock; but the amount which may be obtained by pumping depends entirely on the capacity of the rock as a conduit—that is, on its thickness and the resistance which its texture opposes to the free flow of water. The resistance of the rock, or the friction produced by water in passing through it, might be investigated experimentally in the laboratory, and such an inquiry would be valuable; but a more practical test is afforded by the experience of those who have already tapped the formation by wells and derived a supply from it. A well put down by the town of Rocky Ford gave a measured flow of 68 gallons per minute, or 98,000 gallons per day. A second well in the same town is reported by Mr. C. W. Cressy to yield 157, and a third well 60 gallons. I am informed by Mr. A. J. Hottel, of the Lamar Flouring Mill, that 35,000 gallons are pumped daily from the well at that mill, and that the limit of supply has never been reached, although the head has been drawn down to 150 feet. The first well put down by the Atchison, Topeka and Santa Fe Railroad at La Junta gave a small flow at the surface and yielded 60 gallons per minute by pumping.

There are two considerations of importance affecting the use of such data as have been cited above in estimating the supply to be expected at points heretofore untested. The first is that these wells, like nearly all other wells of the region, end in the first water-bearing sandstone met by the drill. There is reason to believe that in most localities deeper boring would discover a second and often a third sandstone carrying artesian water. Where such lower beds have been examined along the outcrops of the formation their characters indicate that they may prove as valuable as the upper.[2]

[1] Three specimens were found to absorb respectively 12, 16, and 26 per cent of water.

[2] Since this passage was written a partial verification of its prediction has been reported. Two wells recently drilled at La Junta have penetrated the whole of the Dakota formation, finding two water-bearing sandstones separated by a shale bed 130 feet thick. The lower yields the greater volume of water. One of these delivers 50 gallons per minute at about the level of the first La Junta well; the other delivers 20 gallons at a level 135 feet higher.

The second consideration is one of limitation, and pertains to the enlargement of local supply by increasing the number of wells. The experience of many communities has served to demonstrate that every well from which artesian water is drawn diminishes the head or pressure in the neighboring portions of the water-bearing formation, so that a well bored near it can not obtain so much water as it otherwise might. Reciprocally, the drawing of water from a new well diminishes the available supply for all other wells of the vicinity. Where the peculiar value of a flowing well has led to the sinking of a series of other wells in the immediate vicinity, it has always been found that the flow of the older wells is diminished, so that eventually only wells occupying the lowest ground retain sufficient head to discharge at the surface. Pumping then usually follows, with the result that all natural overflow is stopped; and from the continued lowering of the head the cost of bringing the water to the surface gradually increases. If the inhabitants of this district are wise they will profit by the experience of other communities and limit their expectation as to the quantity of water which can be derived from the artesian source beneath. Drawn upon with moderation, it will serve many uses at moderate expense and be of great practical value; but if it is pumped to the extreme limit the head will be drawn so low as greatly to increase the expense of bringing it to the surface, and the yield will not be correspondingly enlarged.

DISTRIBUTION.

The regions already indicated as gathering grounds for artesian water are also to some extent regions available for its exploitation. The sandstones are to such an extent separated by impervious shales that a well started in one of the upper members of the group may, by passing through a shale bed, reach a lower sandstone in which the water is under pressure. This is in general true near the northeastern limit of the area on the St. Charles River, near the northern, western, and southern limits of the area bordering the Huerfano and Apishapa rivers, and near the northeastern, northern, and northwestern limits of the area extending from the Purgatoire River to Clay Creek. In all such cases the depth from the surface will be small, not exceeding 200 or 300 feet.

From these areas northward the depth of the artesian sheet beneath the surface gradually increases, but the rate of increase is irregular, and there are doubtless many localities in which for short distances the depth diminishes northward. The line along which the depth is about 1,000 feet may be approximately and provisionally sketched as follows: It passes through the southwestern part of Pueblo and runs a little west of north up Dry Creek Valley to the vicinity of Blue Hill Spring. In the opposite direction it runs southward, and then more easterly to Undercliff, crosses the Apishapa River not far from the mouth of Mustang Creek, passes north of the Arkansas River a few miles above

Rocky Ford, and continues north of the river to the Kansas line. It is probably as much as 15 miles north of Lamar, but is comparatively near the river in the vicinity of Granada. Between this line and the gathering grounds already mentioned the depth of the artesian water is believed to be everywhere less than 1,000 feet. Farther north it is more than 1,000 feet.

In fig. 49 a rough map is given of the artesian district. A subdistrict is shown in which the depth of water is estimated as less than 1,000 feet, and another in which the depth is estimated as between 1,000 and 2,000 feet. North of the 2,000-foot line, and in an oval tract about Florence the depth to the Dakota water is supposed to be more than 2,000 feet. I confess that I have drawn this map with much reluctance, because it is impossible in such delineation to give adequate expression to doubt, and the data at hand are too imperfect to fix the lines definitely except at a few points. When the region has been thoroughly

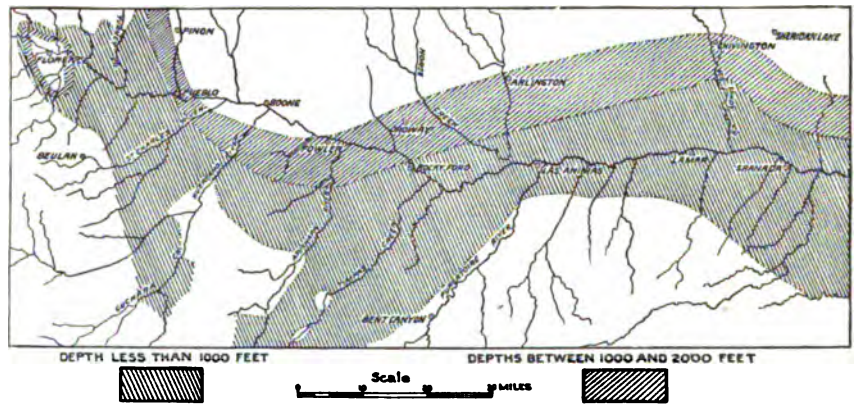


FIG. 49.—The artesian district, showing approximately the area in which the water lies less than 1,000 feet below the surface, and the belts in which its depth is between 1,000 and 2,000 feet.

surveyed, the free-curving boundary lines of each belt as here drawn will be replaced by more sinuous lines, and doubtless the general position of each one will be in some parts materially changed. The reader is warned that he must place no reliance on the local details of the map, but regard it merely as the expression of certain general facts as to the accessibility of the artesian water. The area in which artesian water is available at depths of less than 1,000 feet is nearly 4,000 square miles, and the corresponding area of depths between 1,000 and 2,000 feet is about 1,500 square miles.

The determination of the areas in which the water may be expected to reach the surface without pumping is a more difficult matter. It depends partly on the comparative porosity of the rock in different regions, a character which can not be directly observed; and for this reason trustworthy prediction can not be carried far in advance of experimental boring. There is, however, a general principle in regard

to it which may well be emphasized, for the reason that it is too often disregarded. The absolute head of artesian water, or the height above sea level to which it will rise, depends on conditions existing in the water-bearing rock, and is altogether independent of the local configuration of the ground. It is ordinarily legitimate in any locality to think of that head as a horizontal plane, which may lie beneath the surface of the ground or above it. If the top of a well is below that plane, the water flows; if it is above the plane, pumping is necessary. Therefore, as a rule, it is in each locality more advantageous to start wells on low ground than on high, provided the circumstances under which the water is to be used are such that it will be specially advantageous to have it naturally delivered at the surface.

QUALITY.

The quality of a natural water depends on the character and amount of its impurities, and also, with reference to some uses, on its temperature. Impurities are classed as organic and inorganic, the organic being specially objectionable because they may include the germs of disease, the inorganic being advantageous or disadvantageous, according to the use to which the water is to be applied.

The water derived from the Dakota sandstone is practically free from organic matter and is probably entirely free from living organisms. This is a common character of artesian waters, which are effectually filtered in their long passage through the rocks. Of inorganic matter it contains a moderate amount, but sufficient to place it in the class of mineral waters. In 1,000,000 parts of Mississippi water there are dissolved about 170 parts of various minerals; in the same quantity of St. Lawrence River water about 160 parts. Four analyses of water derived by wells from the Dakota sandstone show 888, 1,341, 1,377, and 2,505 parts of dissolved minerals to 1,000,000 parts of water. The mineral impurity of the Dakota water is thus seen to be from 5 to 15 times as great as in the case of the great rivers of the country. The character, as well as the quantity, of the dissolved impurity varies from place to place, and also from bed to bed, as the different sandstone layers are penetrated. It is stated that in drilling the Grand Hotel well at Pueblo a comparatively pure water was found in an upper bed, and that the strong mineral water now flowing comes from a lower bed. Analyses show that the water of an upper bed obtained by the wells at Rocky Ford and La Junta is only moderately charged, but the water obtained in that district from a lower bed has not yet been tested.

TABLE I.—*Water analyses (results stated in ions).*

[Parts in 1,000,000.]

Substance.	I. Artesian well at Lamar.	II. Artesian well at La Junta.	III. Artesian well at Rocky Ford.	IV. Artesian well at Grand Hotel, Pueblo.
Chlorine (Cl)	33.3	54.0	28.2	277.2
Sulphuric ion (SO_4)	719.4	675.9	453.8	1,180.1
Carbonic ion (CO_3)	114.8	*a* 169.6	*a* 95.9	306.7
Nitric ion (NO_3)	.....	Not est.	.4	.....
Potassium (K)	.....	6.4	7.0	79.2
Sodium (Na)	355.3	360.0	259.2	201.7
Lithium (Li)	.....	Trace.	.5	18.3
Ammonium (NH_4)	.....	(*b*)	.8	.....
Calcium (Ca)	41.6	73.8	14.9	178.1
Strontium (Sr)	.....	(*b*)	.5	.....
Magnesium (Mg)	26.6	20.7	12.4	230.1
Iron (Fe)	.....	*c* .8	*d* 2.8	34.2
Manganese (Mn)	.....	*c* .1	Trace.	.....
Silica (SiO_2)	49.6	*e* 16.1	*f* 11.9	Trace.
Alumina (Al_2O_3)	.....	Trace?	Trace?	.....
Total	1,340.6	1,377.4	888.3	2,505.6

Substance.	V. Carlile Spring.	VI. Iron Duke Spring. Canyon.	VII. Little Ute Spring. Canyon.	VIII. Underflow well at La Junta.
Chlorine (Cl)	117.1	833.0	1,187.8	56.1
Sulphuric ion (SO_4)	238.4	136.0	140.1	550.6
Carbonic ion (CO_3)	459.7	1,217.0	1,109.6	*a* 100.0
Nitric ion (NO_3)	.....	.....	.....	Not est.
Potassium (K)	5.4	Trace.	Trace.	6.2
Sodium (Na)	253.8	1,154.4	1,385.7	143.2
Lithium (Li)	.....	Trace.	Trace.	Trace.
Ammonium (NH_4)	.....	.....	.....	.....
Calcium (Ca)	153.6	214.3	150.0	140.4
Strontium (Sr)	.....	.....	.....	(*e*)
Magnesium (Mg)	55.8	71.3	67.0	35.8
Iron (Fe)	2.5	Trace.	Trace.	.....
Manganese (Mn)	.....	.....	.....	.....
Silica (SiO_2)	.....	.....	.....	15.4
Alumina (Al_2O_3)	.....	.....	.....	.....
Total	1,286.3	3,625.0	4,040.2	1,047.7

a Calculated from normal carbonates.
b Not tested for.
c In deposit.
d 2.6 in deposit.
e 2 in deposit.
f .3 in deposit.

TABLE II.—*Water analyses (results stated in salts).*

[Parts in 1,000,000.]

Substance.	I. Artesian well at Lamar.	II. Artesian well at La Junta.	III. Artesian well at Rocky Ford.	IV. Artesian well at Grand Hotel, Pueblo.
Lithium chloride ($LiCl$)	.....	Trace.	3	108
Potassium chloride (KCl)	.....	12	13	151
Sodium chloride ($NaCl$)	55	80	32	189
Sodium sulphate (Na_2SO_4)	1,030	1,000	671	393
Magnesium sulphate ($MgSO_4$)	29	.....	.....	1,143
Calcium sulphate ($CaSO_4$)	.....	.....	.....	.....
Sodium nitrate ($NaNO_3$)	.....	.....	0.5	.....
Sodium carbonate (Na_2CO_3)	.....	11	67	.....
Ammonium carbonate ($(NH_4)_2CO_3$)	.....	.....	2	.....
Magnesium carbonate ($MgCO_3$)	73	72	43	6
Strontium carbonate ($SrCO_3$)	.....	.....	1	.....
Calcium carbonate ($CaCO_3$)	104	184	37	444
Iron carbonate ($FeCO_3$)	.....	2	6	71
Manganese carbonate ($MnCO_3$)	.....	0.2	Trace.	.....
Silica (SiO_2)	50	16	12	.....
Total	1,341	1,377	888	2,505
Sum of $MgSO_4$, $CaSO_4$, $MgCO_3$, and $CaCO_3$	206	256	80	1,593

Substance.	V. Carlile Spring.	VI. Iron Duke Spring. Canyon.	VII. Little Ute Spring. Canyon.	VIII. Underflow well at La Junta.
Lithium chloride ($LiCl$)	.....	.....	.....	Trace.
Potassium chloride (KCl)	10	.....	.....	12
Sodium chloride ($NaCl$)	185	1,372	1,956	83
Sodium sulphate (Na_2SO_4)	353	201	207	341
Magnesium sulphate ($MgSO_4$)	.....	.....	.....	179
Calcium sulphate ($CaSO_4$)	.....	.....	.....	250
Sodium nitrate ($NaNO_3$)	.....	.....	.....	.....
Sodium carbonate (Na_2CO_3)	154	1,267	1,267	.....
Ammonium carbonate ($(NH_4)_2CO_3$)	.....	.....	.....	.....
Magnesium carbonate ($MgCO_3$)	195	250	235	.....
Strontium carbonate ($SrCO_3$)	.....	.....	.....	.....
Calcium carbonate ($CaCO_3$)	384	535	375	167
Iron carbonate ($FeCO_3$)	5	.....	.....	.....
Manganese carbonate ($MnCO_3$)	.....	.....	.....	.....
Silica (SiO_2)	.....	.....	.....	15
Total	1,286	3,625	4,040	1,047
Sum of $MgSO_4$, $CaSO_4$, $MgCO_3$, and $CaCO_3$	579	785	610	596

I. First artesian well drilled by the town of Lamar. Analysis by Dearborn Drug and Chemical Company, Chicago, Ill.

II. First artesian well at La Junta; drilled by the Atchison, Topeka and Santa Fe Railroad Company. Sampled in September, 1895. Analysis by W. F. Hillebrand, United States Geological Survey. When examined by the chemist the water had deposited a slight brown sediment containing iron, manganese, silica, and a trace of phosphoric oxide. This material is included in the analysis. Free and semicombined CO_2, 124.4. Total CO_2, 250.2.

III. First artesian well at Rocky Ford; near Santa Fe Railroad station. Sampled October, 1895. Analysis by W. F. Hillebrand, United States Geological Survey. Reaction faintly alkaline. Specific gravity at 30.5° C., 1.0008. When received by the chemist the water had deposited a sediment containing silica, iron oxide, and traces of alumina (?) and phosphoric oxide. Free and semicombined CO_2, 106.6. Total CO_2, 176.9. Traces of bromides (?), iodides, and phosphates. Organic matter present, but not estimated. No boron, fluorine, or barium.

IV. Trade name, "Colorado Lithia Water." This analysis, by A. Archie Cunningham, appears in a commercial circular, where it is stated in grains per gallon and in hypothetic combinations. It has been recomputed for this table. Trace of phosphates. No organic matter. Another commercial circular gives a somewhat different analysis, without name of analyst.

V. Carlile Spring, north bank of Arkansas River, 18 miles west of Pueblo. Analysis by O. Loew, reported in Explorations West of the One Hundredth Meridian, volume 3, pages 621 and 622. Sample taken in July, 1874. Trace of organic matter. The spring deposits carbonates of lime and magnesia, building a mound.

VI and VII. Iron Duke and Little Ute Springs, near the State prison, Canyon. Analysis by O. Loew, from samples probably taken in 1874. Reported in Explorations West of the One Hundredth Meridian, volume 3, page 617. Water saturated with free carbonic acid. Traces of iron, potassium, and lithium.

VIII. Surface well on the river bank at La Junta. Water drawn from the underflow of the Arkansas River. Analysis by W. F. Hillebrand, United States Geological Survey. Strong reaction for nitrates, but quantity not estimated.

Tables I and II include not only analyses of the water of artesian wells at Lamar, La Junta, Rocky Ford, and Pueblo, but also of the water of a surface well from which the municipal supply of La Junta was pumped (1895), and the waters of three mineral springs which are probably derived from the Dakota sandstone. The Iron Duke and Little Ute springs, of Canyon, rise from the edge of the Dakota sandstone where it stands at a high angle in the hogback skirting the mountain base. The Carlile Spring rises through Benton shales from an unseen source below, and is provisionally referred to the Dakota sandstone, because that is the first water-bearing rock beneath. The well at La Junta is sunk in the flood plain of the Arkansas River and is supplied by the river water, which undergoes no change except a filtration, eliminating the suspended sediment. It doubtless varies in quality with the volume of the river, being purest when the river is high. The sample was collected in September, 1895, with the river somewhat above mean stage.

These analyses come from various sources, and were originally reported in various ways. To make them comparable they have been reduced to uniformity in mode of statement, and in part recomputed. In Table I the constituents are for the most part stated as ions; in Table II, as

salts. The second is the more usual form of statement, but the first is of higher authority. Each salt is regarded as composed of two ions. For example: Sodium chloride consists of sodium (Na) and chlorine (Cl); calcium carbonate consists of calcium (Ca) and the carbonic ion (CO_3), a compound of carbon and oxygen. In analyzing a water the chemist determines the presence and proportions of a number of ions, but does not know how they are combined in salts; he is not even sure that they exist in such combination. It is true that when water is evaporated to dryness the remaining solids have the constitution of salts, but the relative amounts of different salts thus obtained vary with the conditions under which evaporation takes place; slow and rapid evaporation, evaporation at high and low temperature, and probably also evaporation at high and low pressure, may give different results. When, therefore, the chemist in reporting the results of analyses states the constituents as salts, the combinations he makes are in great measure hypothetical, and different chemists do not reach the same results. The salts of Table II have all been computed according to the same theory, and are therefore comparable one with another, but it is not assumed that the ions are thus combined in the water. The table attempts only to indicate approximately in what form the mineral contents of the water will appear (regardless of water of crystallization) if separated by evaporation at ordinary temperatures and pressures.

In the arrangement of these tables and in the discussions of the data they present, I have availed myself of the expert knowledge and friendly aid of my colleagues in the chemical division of the Geological Survey, especially Prof. F. W. Clarke and Dr. W. F. Hillebrand.

The analyses show that the mineral contents of the Dakota waters include sulphates, carbonates, and chlorides, the sulphates being much the more abundant. The principal metals are sodium, calcium, magnesium, and potassium, their abundance being usually in the order named; silicon and lithium are present in small amount. Of salts, sodium sulphate is most abundant in the wells at Lamar, La Junta, and Rocky Ford; magnesium sulphate and calcium carbonate in the Grand Hotel well, Pueblo; sodium sulphate and calcium carbonate in Carlile Spring; and sodium carbonate and sodium chloride (common salt) in the Canyon springs.

No attempt will be made to set forth the full bearing of these facts on the utilization of the waters, but a few salient points may be noted. The total mineral content is so large as to produce an appreciable and ultimately deleterious deposit in irrigated soil, unless occasionally leached out or neutralized by corrective dressing. The waters of the three springs and of the Grand Hotel well, containing from one-fourth to one-third of 1 per cent of solids in solution, are less desirable than the others for general use as drinking water, but they should nevertheless be preferred to the ground water and river water of the country,

which are easily contaminated by organic poisons. For other domestic uses, and especially washing, the purer waters are in general best, but the various impurities are not equally obnoxious. In a general way, the hardness of water, or its intractability with soap, corresponds to the quantity of its carbonates and sulphates of calcium and magnesium, and judged in this way the Rocky Ford water is best and the Grand Hotel poorest of the series analyzed. For convenience of comparison the sums of these carbonates and sulphates are placed at the bottom of Table II; they constitute an approximate scale of "hardness."

The same scale also serves to show the comparative tendency of the waters to form deposits in boilers, as these salts either separate as such when the water is reduced by boiling or are decomposed and separated in other forms. The water supplied to locomotives of the Atchison, Topeka and Santa Fe Railroad at La Junta was for a number of years drawn from a shallow well near the river (Analysis VIII), and much trouble and expense were occasioned by the rapid formation of boiler scale. In 1895 the water of La Junta artesian well No. 1 (Analysis II) was substituted, with strikingly beneficial results, the cost of cleaning and repairing boilers being reduced more than one-half. Dr. Hillebrand, who analyzed both waters, writes of their comparative value for engine use as follows:

> The mineral constituents of waters most concerned in the formation of boiler incrustations and deposits are certain salts of calcium and magnesium, chiefly the carbonates and sulphates, and in case of magnesium the chloride also. From the "hypothetical combination" column of the surface waters [VIII, Table II] it appears that there are nearly 600 parts per million of calcium and magnesium compounds available for the formation of scale, while in the artesian water [II, Table II] there are at most but 256 parts per million thus available, or less than one-half. For this reason the artesian water should be less troublesome in boilers than the surface waters, and such I understand from you is the case.

Judged by the same criteria, the Lamar artesian water (Analysis I) is of equal value for boiler use with the La Junta, and the Rocky Ford artesian water (Analysis III) is much better than either.

As to the medicinal properties of the Dakota waters, I have not attempted to inform myself. The waters of Carlile Spring and the Grand Hotel well are advertised and sold as therapeutic, and the waters of the Grand Duke and Little Ute springs have given Canyon some reputation as a health resort.

PREDICTION.

The cost of making an artesian well depends largely on the thickness of rock which must be penetrated in order to reach the water. A knowledge of this depth is therefore important to anyone who contemplates drilling. It is also important to know whether the water of a well drilled at a given point may be expected to flow out at the surface or only to rise to some level below the surface. Prediction as to these two points will doubtless have greatest value if made by a geologist

who has personally studied the district, but in many cases the resident can be his own geologist, and it is worth while to point out how he can help himself to the knowledge he desires.

The general arrangement of the rocks is shown in the sections of Pl. LXVIII, and some general facts as to the depth of artesian water are embodied in fig. 49; but there are many important details of which these diagrams take no account, and it is also true that the geologic work on which they are based was not sufficiently thorough to give full warrant even to the lines which have been drawn. Another part of the work, however—the determination of the sequence and thickness of the rocks—was performed in a more satisfactory manner, and its results, when properly applied by the seeker for artesian water, may aid him in making a useful estimate of the cost of obtaining it. In the description of the Cretaceous formations, in the earlier sections of this report, care was taken to give prominence to such special features as may serve to distinguish particular rocks wherever they are found at the surface. Their general characters—as sandstone, shale, limestone—were given, the special modes in which the two principal limestones break up at the surface were described, pictures were given of the fossil shells most likely to be found in each of the limestones and also in certain shales; small nodules contained in one of the limestones were pictured, and a type of hill produced by the presence of hard masses in one of the shales was figured. If by the aid of these characters the inquirer can determine the particular formation which exists at the surface at any point, he can then, by the aid of fig. 46, tell how deep it will be necessary to drill in order to reach the first water-bearing sandstone.

Often there are no good exposures of rock at the place where a well is desired, and the nearest outcrop of recognized rock is so far away as to leave the geologic relations of the locality in doubt. In such cases it is well to be able to recognize different formations as the drill descends. For this purpose it is advantageous to compare the material brought up by the sand pump with samples of the drillings obtained at various depths from some other well of the district, and by means of such comparison it will often be possible to make a close estimate of the remaining distance to the water-bearing rock. When such comparison can not be made, there is still one bed which can always be recognized, provided the work is begun at some level above it, and that is the limestone at the base of the Timpas formation. Its fragments are almost white, and are thereby distinguished from nearly all other rocks of the district. The thickness of the bed, from 35 to 50 feet, is much greater than that of any other limestone of the district. To determine that the chips are actually of limestone a few of them should be placed in a glass of dilute hydrochloric (muriatic) acid. The acid attacks the limestone, changing it to chlorides of calcium and magnesium, which are dissolved, and setting free carbonic acid gas, which escapes in bubbles. When the bubbling has ceased it will be found that the limestone chips have com-

pletely disappeared, leaving the liquid clear or very slightly cloudy. If flakes of shale are put into the acid, there is usually some effervescence, because most of the shales of the district contain a small amount of calcium and magnesium carbonates; but after the effervescence has ceased it will be found either that the flakes retain their original form and size or else that they have been broken up into minute particles, so as to make the liquid muddy. Such a test will be useful in case there is doubt as to whether the limestone has been reached. The distance from the bottom of this limestone to the first water horizon is about 450 feet.

The question whether the water when reached will rise higher than the surface, or not so high, is a question of head. As the water lies in the sandstone before it is tapped it presses against the overlying formation, and that pressure is measurable, like the pressure of steam, in pounds per square inch. For every pound of pressure the water is able to rise 2.3 feet above the top of the water-bearing stratum. If the overlying rocks be pierced and a tube fitted to the opening and carried indefinitely upward, then the water will rise in this tube to a height corresponding to the pressure exerted at the base. At every height the water will press on the tube, but the amount of such pressure will gradually diminish upward, so that at the top of the water column the pressure will be nil. A drilled well from which water naturally flows may be compared to such a tube as has been described. If it be continued by a pipe above the ground, the head can be determined by finding how high the water rises; but in case it is not practicable to do this the same result may be accomplished by cutting off the flow of the well and attaching a pressure gage; then for each pound of pressure shown by the gage 2.3 feet must be added to the height of the position of the gage in order to compute the height of the head. The ordinary steam gage, if new, is sufficiently accurate for this purpose. It will usually be found that after the flow of a well is stopped the pressure increases somewhat rapidly at first, and then more slowly. By watching the gage from hour to hour it will be seen that the increase of pressure finally becomes inappreciable, and the reading may then be taken.

For various reasons the pressure of artesian water on the walls of its reservoir varies from point to point, and the absolute height to which the Dakota water will rise is not everywhere the same. If for each point of the reservoir a point were marked somewhere above indicating the head of the water, then these latter points would together constitute a surface sloping in various directions. In some places this imaginary surface would stretch above the surface of the soil, and there flowing wells might be obtained; elsewhere it would pass through the rocks beneath the soil, and there only pumping wells might be secured. Of the actual slopes of such a surface little is known as yet, and for practical purposes it is at present best to assume that within any limited

district, such as might be called a neighborhood, the surface is horizontal. On this assumption the head determined for an existing well shows the head which may be expected for a new well in the same neighborhood. If the water in an existing well does not rise to the surface, but stands at a certain distance below, then it is evident that one must go down hill in order to find a place where a flowing well can be made. If the existing well furnishes water freely at the surface, then by measuring its head one can determine how far up hill a well can be located without losing the probability of a surface discharge.

Where there are several water-bearing rocks within reach of the drill, each water sheet will ordinarily have a different head from the others, and under ordinary circumstances the head of the lowest sheet will be the greatest. Information as to the several pressures exerted by water from different strata is therefore of importance to the community.

GROUND WATER.

The arrangement of strata necessary to the retention of water under pressure is comparatively rare, so that artesian water is the exception rather than the rule; but the conditions favorable to the accumulation of ground water are widespread. The bed rock of a country is usually overlain by a deposit of loose material, such as loam, sand, or gravel. So much of the water of rain as escapes evaporation and does not immediately run away over the surface sinks into this loose material and finds its way gradually downward until it meets with some impervious formation. Its downward course is then checked, and it either remains stagnant, as a sort of subterranean lake, or flows slowly in some direction, as a sort of subterranean stream.

GENERAL CONDITIONS.

The quantity of ground water in the ground, its depth beneath the surface, its quality, and the direction and rate of its flow depend on a variety of circumstances. The supply is necessarily limited by the rainfall, but is usually far less in amount, because a portion of the falling rain runs away and another portion is evaporated directly from the surface of the soil. A very porous soil captures more of the rain than can be received by a soil of fine texture, and it has the further advantage that it permits so free a flow that much of the water descends quickly to the reservoir beneath, whereas a less pervious soil tends not only to hold the water near the surface, but to return it to the surface as evaporation progresses. Where the layer of loose material is shallow the circulation of dry air through it may carry away ground water, but where it is deep such loss is practically prevented.

Digging down through the surface layer of earth, one may often find it dry or moist or alternately dry and moist, and if these characters continue until impervious rock is reached, there is said to be no ground

water—that is to say, there is no water which will accumulate in a well. Often, however, the lower part of the layer is not merely moist, but is filled with water, and wherever it is thus saturated the water will flow from it, filling the lower part of the excavation. The surface separating saturated earth from earth that is merely moist is the upper limit of the ground water, and marks everywhere the height at which water will stand in a well. It is called the "water table," or, more appropriately, the "water plain." It is usually not a level surface, but slopes in various ways, and the direction of its slope is always the direction in which the ground water flows. In some localities the water plain may be parallel to the surface of impervious rock beneath; in other localities it may be parallel to the surface of the ground; but usually it is an independent surface, following its own laws of slope.

The rate of movement of ground water is very slow as compared to the flow of a surface stream. Its slowness depends on the great friction produced by the movement of water through narrow passages. Sand permits more rapid currents than fine earth, and the currents through clean gravel are much more rapid than through sand. The coarser formations are thus not only more receptive of water, but transmit it more quickly and part with it more easily.

The quality of ground water varies greatly from place to place. Where the supply is large and the flow comparatively rapid, the more soluble mineral constituents of the soil are soon leached out, and the water afterwards carries only a small amount of the less soluble materials. Where the supply is small or the water nearly stagnant, it may contain a large amount of the more soluble salts. Ground waters usually contain a notable quantity of organic matter—material derived from the decomposition of animal and vegetable tissues—and with these are associated microscopic organisms. Such ground waters as are replenished from the soil directly above them by the water of every storm are peculiarly susceptible to such contamination.

WATER OF THE UPLAND SANDS.

In the district under consideration the most important reservoir of ground water is the group of deposits already described as the upland sands. At most points wells sunk through these sands find water before reaching the bed rock, and the presence of the water is otherwise demonstrated by the springs occurring at the margins of the formation. Little is known as to the quantity of water contained in the sands. The wells afford little information, because the digging is usually stopped soon after the water plain is reached; and only a small portion of the evidence they are capable of affording was gathered during my work. In some places the wells show that the ground water is a very thin sheet, and in others that it is altogether absent.

Some of the wells pass through a great depth of fine earth that seems entirely dry, and in such localities it may be doubted whether

any of the rain water ever finds its way to the base of the formation. Elsewhere the greater part of the formation is moist to the top. It seems, therefore, probable that the ground water is not replenished by the rains of the whole district covered by the upland sands, but only in those tracts where the upper part of the formation has a somewhat open texture; but no progress has been made in determining the extent and position of such areas of supply. The principal body of upland sands extends northward and northwestward beyond the region of observation, and as the country rises in that direction search for the sources of supply would naturally be directed that way. There is a popular impression in some parts of Kansas that the water enters the formation on the slopes of the Rocky Mountains, where the rainfall is great, but there is good reason to regard this view as erroneous. There is probably no place where the formation extends so far west as the flanks of the mountains.

A long line of springs marks the southern edge of the northern area. Among them may be mentioned the Nusbaum Spring, a few miles northeast of Pueblo; a group of springs in the banks of Chico and Black Squirrel creeks near their junction; Antelope Spring, at the head of Bob Creek Valley, and the great spring near Coolidge, Kans. Horse Creek, Adobe Creek, Rush Creek, and Big Sandy Creek probably derive their chief supply from the same source. None of these streams are so large as to carry water at the surface the whole year, but there is always a considerable body of underflow beneath their sandy beds. South of the Arkansas the upland sands nourish the springs at the head of Clay Creek, and sustain Two Butte Creek, which, like the more northerly creeks, carries most of its water in the sands of its bed. It is reported of these springs that they are uniform in flow from season to season and from year to year. This character indicates that the principal supply in each case comes from a considerable distance, or, what amounts to the same thing, that it is derived from a large tract of country. The volume of the creeks is much more variable, doubtless because it depends in part on that portion of the rain water which flows down the surface of the slopes. No analyses have been made of these waters, but they differ from the artesian waters in that they have no notable taste. Their behavior with soap indicates that they are in general somewhat charged with the less soluble salts.

The water obtained by wells shows greater variety than the spring water, and some of it is both unpalatable and unwholesome. The differences doubtless depend somewhat on the character of the underlying rock, but are probably more closely related to the volume of flow. Where the flow is comparatively rapid the chlorides and more soluble sulphates have already been leached out; but where the currents are feeble the leaching is still in progress. Only the stronger streams give rise to springs, and the spring waters are therefore comparatively pure. Wells may draw their supply from the underground currents which

end in springs, and thus obtain water of the same quality, or they may reach only the comparatively stagnant portions of the underground sheet.

WATER OF THE TERRACES.

There may be some instances in which the sands of the Arkansas terraces, resting against the slopes of the Dakota sandstone, receive water from that formation; but in general their supply comes only from the rain on their surfaces, and the gathering ground is too small to create a free circulation. I am not acquainted with any springs which issued from such terrace formations before the institution of irrigation, and many wells sunk in the terraces are unsuccessful. The lower terraces are, however, much used for irrigation, as they afford gently sloping bodies of land to which the river water can be carried by canals of moderate length. When they are irrigated, the sands and gravels which cap them gradually imbibe the water of irrigation and eventually become well charged with it. The water plain usually rises to within a few feet of the surface, and springs abound along the bluffs that margin the terraces. Some of the wells afford fresh water; others, water that is notably saline or alkaline; and individual wells often change their character as the development of irrigation progresses. The marginal springs are usually of poor quality and are often highly charged with the more soluble salts. It seems evident that the circulation thus artificially introduced is leaching soluble material not only from the sands and gravels which cap the terraces, but also from the upper part of the underlying shales, and many years must elapse before this process will have advanced so far that the water of the marginal springs is palatable.

WATER OF THE DUNE SANDS.

The regions of wind-blown sand are better adapted than most parts of the district to the reception and storage of rain water. Not only is the surface soil of such open texture as to absorb the whole of the gently falling rain, but the surface undulates in such a way as to inclose numerous basins in which the water of the more violent storms is impounded until it can soak into the ground. Nevertheless, the presence of ground water has rarely been demonstrated in such districts, because the deeply porous soil unfits it for irrigation, and its natural vegetation is of a character affording but lean pasturage. The dune tracts are therefore mainly uninhabited, and the underlying water is not utilized.

UNDERFLOW OF RIVERS AND CREEKS.

All of the larger streams of the district flow through bottom lands of loam, sand, and gravel. These bottom lands are composed of materials which have been transported and deposited by the streams themselves. The action of streams, as already explained, deposits

comparatively coarse material at bottom and comparatively fine material at top, so that beneath the bottom lands there are usually porous beds, such as coarse sand or gravel. Sometimes these coarse beds extend no deeper than the bottom of the stream channel, but more often they are of greater depth. In either case they constitute a reservoir for water. Where the surface flow of a stream is not continuous, but depends on occasional storms, a part of the storm water is received by the stream sands and is thus stored. It also flows slowly through the sand in the direction of the descent of the valley. The stream sands may thus be regarded from one point of view as reservoirs, and from another as the channels of underground streams.

That the water actually flows is shown by the condition of the larger creeks and smaller rivers during dry seasons. Where the bottom land or flood plain is broad no water is seen at the surface; but where it is narrowly hemmed in by canyon walls the bottom of the channel may be occupied by a running stream. The water which thus at points of constriction appears at the surface may be seen to issue from the sands of the valley above the constriction and to disappear again in the sands below. It is evidently part of an underground stream brought locally to the surface by the narrowing of its channel. The quantity of flowing water thus revealed is always very small as compared to the capacity of the superficial stream channel, and it is also small as compared to the capacity of the sand bed or subterranean channel above and below the point of constriction.

The underflow of the Arkansas River is rarely demonstrated by the phenomena of disappearance and reappearance, but there can be no doubt that it is greater than that of any tributary. The body of sand is in general broad, it is usually somewhat deeper than the surface water channel, and it is so coarse as to imbibe water freely. Regarded as a reservoir, it is unquestionably of great importance, and its water may also prove valuable as a flowing stream.

Considered as a reservoir, the Arkansas sands have a breadth approximately as great as the bottom lands and a depth ranging from 5 to 20 or 30 feet. They are in general charged to a level somewhat above the low-water surface of the stream. In time of flood there must be a lateral flow from the stream channel into the sands, and in time of drought a movement in the opposite direction. Where irrigation is practiced, the river sands also receive some of the seepage from the fields, and their water plain is thereby raised.

In connection with the present work no attempt has been made to estimate the volume of available water contained in this reservoir. Such a computation would require not only the measurement of the area and depth of the saturated sands, but a comprehensive knowledge of their ability to absorb and deliver water. Very little observation is necessary to show that the sands are exceedingly variable in texture, and an estimate which failed to take account of this variability might

easily go far astray. In order to obtain some general idea of the quality of the river sand in this respect, Mr. Newell collected two samples from the river bed at Lamar, the one representing the coarser and the other the finer of the sands there exposed. The coarser sample was afterwards tested by Mr. G. W. Stose, in the following manner: After being thoroughly dried it was saturated with water, and the quantity of water received was determined by weighing. The vessel containing it was then punctured at the bottom, so as to permit the water to drain away, and after a lapse of several days the loss of water was determined by another weighing. It was then found that the sand had received 29 per cent of its volume of water, but afterwards parted with only one-third of the water received, equivalent to 10 per cent of the whole volume of sand.

The conditions under which the experiment was tried represent fairly well the ordinary conditions under which water is drawn by wells from the river sands, and if there was good reason to believe that the sample was properly representative of the river sands in general, we might conclude that each cubic foot of saturated sand along the river contains, on the average, one-tenth of a cubic foot of available water. A sample of sand taken from one of the ancient deposits of the Arkansas River, now exposed in the face of "the Mesa," near Santa Fe avenue in Pueblo, was similarly treated, being found to absorb 29 per cent of water and deliver only 3 per cent. A sample from the bed of Big Sandy Creek, near Water Valley, gave a much better result, absorbing 30 per cent of water and returning 21 per cent.

It is even more difficult to obtain a just estimate of the volume of the river-sand water considered as a stream. The speed with which ground water flows depends on the relation of the impelling force to the resistance. The force is measured by the slope of the water plain, and that, in the case of the Arkansas River, is from 7 to 15 feet per mile. The resistance varies in some complex way with the texture of the sand; it also varies with the rate of flow, but not in a simple arithmetical way. A thorough treatment of the subject would therefore require a knowledge of the law under which the velocity of water is determined by the impelling force and of the texture of the sand, and also a local knowledge of the variations of sand texture in different parts of the section. It is to be hoped that both these subjects of inquiry will soon be taken up by the division of the Survey specially charged with the investigation of water supply, but at the present time there is no evidence on which to base a definite judgment. In any case the volume of water flowing through any given cross section in a unit of time must be very much smaller than the average discharge of the surface stream.

The underground water of the stream beds is almost as variable in quality as that of the upland sands, and, except for suspended and visible impurity, is quite as variable as the overground water of the streams. In general the water of the longer streams is purer near its source than after it has flowed for a great distance and been reduced

by evaporation. Where irrigation is practiced, there is still further deterioration by reason of the mineral matter brought from the irrigated soils and subsoils. The saline and bitter waters which issue from the springs along the margins of the irrigated terraces are perpetually contaminating the river waters, both above ground and below, and along the lower reaches of the river it must be expected that the quality of the underflow will for many years steadily deteriorate. Changes of this sort have been reported by some of the older residents, but determinations depending on taste and other matters of ordinary personal observation are subject to considerable question. A more authoritative observation is that made by the officers of the Santa Fe Railroad at La Junta, where the difficulties occasioned by the deposit of mineral impurities in boilers are reported to have steadily increased for years, until the growing expense occasioned by them led to the search for a better water supply by means of the drill.

ACKNOWLEDGMENTS.

My indebtedness to various individuals and publications for assistance and information has been acknowledged on the preceding pages, but there are certain obligations which could not be conveniently or adequately recognized in such way. In the preparation of the manuscript I have frequently conferred with my colleague, Mr. F. H. Newell, and have drawn freely on his expert knowledge of the general subject of water supply. The names of fossils are given on the authority of Mr. T. W. Stanton, and he has kindly assisted me in the selection of specimens to be figured in the preparation of some of the illustrations. In addition to the gentlemen whose names are mentioned in the report, I have been materially assisted in my search for information as to artesian wells by Mr. C. H. Small, of Pueblo; Hon. G. W. Swink, of Rocky Ford; Mr. W. W. Jones, of Granada; and Mr. A. D. Jones, of Coolidge.

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